GOVERNANCE OF GLOBALIZED WATER RESOURCES

THE APPLICATION OF THE WATER FOOTPRINT TO INFORM CORPORATE STRATEGY AND GOVERNMENT POLICY

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GOVERNANCE OF GLOBALIZED WATER RESOURCES

THE APPLICATION OF THE WATER FOOTPRINT TO INFORM CORPORATE STRATEGY AND GOVERNMENT POLICY

DISSERTATION

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the degree of doctor at the University of Twente,

on the authority of the rector magnificus,

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by

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born on 23 June 1979
in Ankara, Turkey

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Ertug Ercin
Enschede, July 2012

Summary

Managing the water footprint of humanity is something in which both governments and businesses have a key role. The actual reduction of humanity's water footprint depends on the combination of what governments, businesses and consumers do and how their different actions reinforce (or counteract) one another. Therefore, we need improved understanding of how water footprint reduction strategies by governments on the one hand and companies on the other hand can reinforce or counteract each other in achieving actual reduction of humanity's water footprint. The objective of this thesis is to understand how the water footprint concept can be used as a tool to inform governments and businesses about sustainable, efficient and equitable water use and allocation. This study alternately takes a governmental and a corporate perspective, because both actors have a significant role in mitigating the water footprint of humanity and there is a strong interaction between the roles and responsibilities of both actors.

This thesis starts with assessments from business perspective. Chapters 2 and 3 present two applications of WF for companies. The thesis continues with WF applications from governmental perspective. Chapter 4 shows an application of the WF at national level. Chapter 5 analysis how WF scenarios can inform national policy making in the long term. After governmental studies, the thesis explores to which extent we can draw lessons from the carbon footprint case in terms of adoption of policy responses for governments and companies (Chapter 6). It finishes with the assessment of how the WF can be used in combination with other environmental footprint indicators in a context of exploring the relation between economics and environmental pressure (Chapter 7). The main findings are summarized below, following the chapter-setup of the thesis:

The water footprint of soy milk and soy burger and equivalent animal products: As all human water use is ultimately linked to final consumption, it is interesting to know the specific water consumption and pollution behind various consumer goods, particularly for goods that are water-intensive, such as foodstuffs. The water footprint of 1 litre soy milk is 297 litres, of which 99.7% refers to the supply chain. The water footprint of a 150 g soy burger is 158 litres, of which 99.9% refers to the supply chain. Although most companies

focus on just their own operational performance, this study shows that it is important to consider the complete supply chain. The major part of the total water footprint stems from ingredients that are based on agricultural products. In the case of soy milk, 62% of the total water footprint is due to the soybean content in the product; in the case of soy burger, this is 74%. Thus, a detailed assessment of soybean cultivation is essential to understand the claim that each product makes on freshwater resources. This study shows that shifting from non-organic to organic farming can reduce the grey water footprint related to soybean cultivation by 98%.Cow's milk and beef burger have much larger water footprints than their soy equivalents. The global average water footprint of a 150 g beef burger is 2350 litres and the water footprint of 1 litre of cow's milk is 1050 litres.

The water footprint of a sugar-containing carbonated beverage: The water footprint of the beverage studied has a water footprint of 150 to 300 litres of water per 0.5 litre bottle, of which 99.7-99.8% refers to the supply chain. The results of this study show the importance of a detailed supply-chain assessment in water footprint accounting. The study shows that the water footprint of a beverage product is very sensitive to the production locations of the agricultural inputs. Even though the amount of sugar is kept constant, the water footprint of our product significantly changes according to the type of sugar input and production location of the sugar. Additionally, the type of water footprint (green, blue and grey) changes according to location, which are mainly driven by the difference in climatic conditions and agricultural practice in the production locations. These results reveal the importance of the spatial dimension of water footprint accounting. It shows that even small ingredients can significantly affect the total water footprint of a product. On the other hand, the study also shows that many of the components studied hardly contribute to the overall water footprint. This is the first study quantifying the overhead water footprint of a product. Strictly spoken, this component is part of the overall water footprint of a product, but it was unclear how relevant it was. This study reveals that the overhead component is not important for this kind of studies and is negligible in practice.

The water footprint of France: The total water footprint of production and consumption in France is 90 billion m^3/year and 106 billion m^3/year respectively. The blue water footprint of production is dominated by maize production. The basins of the Loire, Seine, Garonne, and Escaut have been identified as priority basins where maize and industrial production are the dominant factors for the blue water scarcity. About 47% of the water footprint of French consumption is external and related to imported agricultural products. Cotton, sugar cane and rice are the three major crops with the largest share in France's external blue water footprint of consumption and identified as critical products in a number of severely water-scarce river basins. The basins of the Aral Sea and the Indus, Ganges, Guadalquivir, Guadiana, Tigris & Euphrates, Ebro, Mississippi and Murray rivers are some of the basins that have been identified as priority basins regarding the external blue water footprint of French consumption. The study shows that analysis of the external water footprint of a nation is necessary to get a complete picture of the relation between national consumption and the use of water resources. It provides understanding of how national consumption impacts on water resources elsewhere in the world.

Water footprint scenarios for 2050: This study develops water footprint scenarios for 2050 based on a number of drivers of change: population growth, economic growth, production/trade pattern, consumption pattern (dietary change, bioenergy use) and technological development. Our study comprises two assessments: one for the globe as a whole, distinguishing between 16 world regions, and another one for Europe, whereby we zoom in to the country level. This study shows how different driver will change the level of water consumption and pollution globally in 2050. These estimates can form an important basis for a further assessment of how humanity can mitigate future freshwater scarcity. We showed with this study that reducing humanity's water footprint to sustainable levels is possible even with increasing populations, provided that consumption patterns change. This study can help to guide corrective policies at both national and international levels, and to set priorities for the years ahead in order to achieve sustainable and equitable use of the world's fresh water resources.

Understanding carbon and water footprints: The carbon footprint has become a widely used concept in society, despite the lack of scientifically accepted and universally adopted guidelines. Different stakeholders use the term with loose definitions or metaphorically, according to their liking. The water footprint is becoming popular as well, and there is substantial risk that it goes the same route as carbon footprint. The aim of this study to extract lessons that may help to reduce the risk of losing the strict definition and interpretation of the water footprint by understanding the mechanisms behind the adoption of carbon footprint. Reduction and offsetting mechanisms are applied and supported widely in response to the increasing concern about global warming. However, the effective reduction of humanity's carbon footprint is seriously challenged because of two reasons. The first is the absence of a unique definition of the carbon footprint, so that reduction targets and statements about carbon neutrality are difficult to interpret, which leaves room for making developments show better than they really are. The second problem is that existing mechanisms for offsetting leave room for creating externalities and rebound effects. In the case of the water footprint, the identification of how to respond is still under question. The strategy of water offsetting will face the same problem as in the case of carbon, but there is another one: water offsetting can only be effective if it takes place at the specific locations and in the specific periods of time when the water footprint that is to be offset takes place. It is argued that the weakness of offsetting in the case of carbon footprint shows that applying both offsetting and neutrality in water footprint cannot be effective solutions and ideas. A more effective tool is probably direct water footprint reduction targets to be adopted by both governments and companies.

Integrating ecological, carbon and water footprint into a "footprint family" of indicators: In recent years, attempts have been made to develop an integrated footprint approach for the assessment of the environmental impacts of production and consumption. In this chapter, we provide for the first time a definition of the "footprint family" as a suite of indicators to track human pressure on the planet and under different angles. It builds on the premise that no single indicator per se is able to comprehensively monitor human impact on the environment, but indicators rather need to be used and interpreted jointly. The paper concludes by defining the "footprint family" of indicators and outlining its appropriate policy use for the European Union (EU). This study can be of high interest for both policy makers and researchers in the field of ecological indicators, as it brings clarity on most of the misconceptions and misunderstanding around footprint indicators, their accounting frameworks, messages, and range of application.

1 Introduction

Water plays a key role on our planet. Access to sufficient freshwater with adequate quality is a prerequisite for human societies and undisturbed natural water flows are essential for the functioning of ecosystems that support life on Earth (Costanza and Daly, 1992). Throughout history, the scale of man's influence on the quality and quantity of freshwater resources has grown. Today, human use of freshwater is so large that water scarcity and competition over water among users has become clearly visible in many parts of the world. Therefore, it is important to understand what the driving forces behind human's demand for water are.

At present, irrigated agriculture is responsible for about 70% of all freshwater abstractions by humans (Bruinsma, 2003; Shiklomanov and Rodda, 2003; UNESCO, 2006; Molden, 2007) while it is responsible for roughly 90% of worldwide consumptive use of freshwater (Hoekstra and Mekonnen, 2012a). In addition to agriculture, industries and households use substantial amounts of water and contribute significantly to water pollution (WWAP, 2009). In many places, urban areas, industry, agriculture, and natural ecosystems compete for freshwater (Rosegrant and Ringler, 1998; UNESCO, 2006; Anderson and Rosendahl, 2007).

Water resources policies have traditionally focused on managing direct water withdrawals by 'water users'. However, it has been shown that this approach is limited. Final consumers, retailers, traders and businesses as *indirect* water users have stayed out of the scope of water policies. By neglecting the connection between these actors and water consumption and pollution along their supply chains, one limits options for comprehensive water governance (Hoekstra et al., 2011). As all human water consumption is ultimately linked to final consumption, it is important to use indicators that make this connection clear, thereby enabling the design of water policies targeted at sustainable and equitable water use.

Since the Dublin Conference in 1992 (ICWE, 1992), there is consensus that the river basin is the appropriate unit for analysing freshwater availability and use. However, today the idea of water being a local issue is changing. In our interconnected world, each river basin is connected to producers, traders and consumers around the world. Therefore, the use of water in a basin is influenced by trade patterns and can be affected by consumption far beyond the basin's borders (Hoekstra and Chapagain, 2008). It is important to understand that not only local but also global forces have a significant influence on the use of water and water scarcity level within a river basin.

The background of this thesis is that it is becoming increasingly important to put freshwater issues in a global context. Local water depletion and pollution are often closely tied to the structure of the global economy. With increasing trade between nations and continents, water is more frequently used to produce export goods. International trade in commodities implies long-distance transfers of water in virtual form, where virtual water is understood as the volume of water that has been used to produce a commodity and that is thus virtually embedded in it. Knowledge about the virtual-water flows entering and leaving a country can cast a completely new light on the actual water scarcity of a country. A second starting point of this thesis is that it becomes increasingly relevant to consider the linkages between consumer goods and impacts on freshwater systems. This can improve our understanding of the processes that drive changes imposed on freshwater systems and help to develop policies of wise water governance.

1.1 The water footprint concept

Understanding the consequences of human appropriation of freshwater resources requires an analysis of how much water is needed for human use versus how much is available, where and when (Rijsberman, 2006; Hoekstra and Chapagain, 2007; Lopez-Gunn and Ramón Llamas, 2008; Rosegrant et al., 2009). Uncovering the link between consumption and water use is vital to formulate better water governance. The 'water footprint' concept was primarily formulated in the research context, to study the hidden links between human consumption and water use and between global trade and water resources management (Hoekstra and Chapagain, 2007). The concept helps us understand the relationships between production, consumption and trade patterns and water use and the global dimension in good water governance.

The water footprint is an indicator of freshwater use that looks not only at direct water use of a consumer or producer, but also at the indirect water use. The water footprint can be regarded as a comprehensive indicator of freshwater resources appropriation, next to the traditional and restricted measure of water withdrawal. The water footprint of a product is the volume of freshwater used to produce the product, measured over the full supply chain. It is a multi-dimensional indicator, showing water consumption volumes by source and polluted volumes by type of pollution; all components of a total water footprint are specified geographically and temporally. The blue water footprint refers to consumption of blue water resources (surface and ground water) along the supply chain of a product. 'Consumption' refers to loss of water from the available ground-surface water body in a catchment area. Losses occur when water evaporates, returns to another catchment area or the sea or is incorporated into a product. The green water footprint refers to consumption of green water resources (rainwater stored in the soil as soil moisture). The grey water footprint refers to pollution and is defined as the volume of freshwater that is required to assimilate the load of pollutants given natural background concentrations and existing ambient water quality standards (Hoekstra et al., 2011).

The water footprint was developed as an analogy to the ecological footprint concept. It was first introduced by Hoekstra in 2002 to provide a consumption-based indicator of water use (Hoekstra, 2003). It is an indicator of freshwater use that shows direct *and indirect* water use of a producer or consumer. The first assessment of national water footprints was carried out by Hoekstra and Hung (2002). A more extended assessment was done by Hoekstra and Chapagain (2007; 2008) and a third, even more detailed, assessment was done by Hoekstra and Mekonnen (2012a).

1.2 Water footprint assessment

Water footprint assessment is an analytical tool; it can be instrumental in helping to understand how activities and products relate to water scarcity and pollution and related impacts and what can be done to make sure that activities and products do not contribute to unsustainable use of freshwater. As a tool, water footprint assessment provides insight; it does not tell 'what to do'. Rather it helps to understand what can be done.

Water footprint assessment refers to the full range of activities to (i) quantify and locate the water footprint of a process, product, producer or consumer or to quantify in space and time the water footprint in a specified geographic area, (ii) assess the environmental, social and economic sustainability of this water footprint and (iii) formulate a response strategy (Hoekstra et al., 2011). Broadly speaking, the goal of assessing water footprints is to analyse how human activities or specific products relate to issues of water scarcity and pollution and to see how activities and products can become more sustainable from a water perspective.

1.3 Problem statement

Managing the water footprint of humanity is something in which both governments and businesses have a key role. The actual reduction of humanity's water footprint depends on the combination of what governments, businesses and consumers do and how their different actions reinforce (or counteract) one another. Therefore, we need improved understanding of how water footprint reduction strategies by governments on the one hand and companies on the other hand can reinforce or counteract each other in achieving actual reduction of humanity's water footprint.

1.3.1 Business perspective

Water is crucial for the economy. Virtually every economic sector, from agriculture, electric power, manufacturing, beverage and apparel to tourism, relies on freshwater to sustain its business. Yet water is becoming scarcer globally and every indication is that it will become even more so in the future. Decreasing availability, declining quality, and growing demand for water are creating significant challenges to businesses and investors who have traditionally taken clean, reliable and inexpensive water for granted. These problems are already causing decreases in companies' water allotments, shifts toward full-cost water pricing, more stringent water quality regulations, growing community opposition, and increased public scrutiny of corporate water practices.

For many companies, freshwater is a basic ingredient for their operations, while effluents may pollute the local ecosystem. Various companies have addressed these issues and formulated proactive management strategies (Gerbens-Leenes et al., 2003). Failure to manage the freshwater issue raises four serious risks for a company: damage to the corporate image, the threat of increased regulatory control, financial risks caused by pollution, and insufficient freshwater availability for business operations (Rondinelli and Berry, 2000; WWF, 2007). Therefore, the efficient use of freshwater and control of pollution is often part of sustainability issues addressed by business. However, how to address the sustainability of the full supply chain of products from a freshwater point of view is still an open question to most companies.

1.3.2 Governmental perspective

Recently, it has become evident that the water problems of a country can no longer be solved by the traditional ‘production perspective’ alone. Due to the globalised structure of trade, the ‘real’ consumers of the water resources are often not the victims of the impacts caused by their consumption. Traditionally, national governments do not consider the virtual water flows through imports in their national water policies and exclude water use and its impacts outside their country to support national consumption. In order to support a broader sort of analysis and better inform decision-making, this traditional way of thinking in national water policy should be extended. A responsible and fair water policy would hence have to have an international component (Hoekstra et al., 2011).

Traditional national water use accounts only refer to the water withdrawals for various sectors within a country. They do not distinguish between water use for making products for domestic consumption and water use for producing export products. They also exclude data on water use outside the country to support national consumption. In order to support a broader sort of analysis and better inform decision making, national water use accounts need to be extended. How to do this, and how to use those accounts in informing the national policy, is an unanswered question for governments, that have just started to become aware of the international dimension of good water governance.

1.3.3 Need for set of indicators

Solving the sustainability challenge requires an approach that considers all aspects of human pressure on the world's natural resources. An integrated ecosystem approach is required in order to tackle multiple issues concurrently, and help to avoid additional costs that are created when taking measures that reduce one sort of pressure on the environment but then appear to increase another sort of pressure. This can happen, for example, when policies to reduce carbon footprint lead to an increase of the water footprint. Therefore, a set of indicators is needed to account for the environmental consequences of human activities. The water footprint is able to capture just one aspect of the full complexity of sustainable development: human appropriation of freshwater resources. The water footprint should be addressed with other footprint indicators (carbon and ecological footprints) in order to more comprehensively monitor the environmental pillar of sustainability.

In addition, it can be useful to examine whether experiences with the way the global society applies and responds to one environmental pressure indicator can provide lessons for how we can effectively use and respond to another indicator.

1.4 Objective

The objective of this thesis is to understand how the water footprint concept can be used as a tool to inform governments and businesses about sustainable, efficient and equitable water use and allocation. This study alternately takes a governmental and a corporate perspective, because both actors have a significant role in mitigating the water footprint of humanity and there is a strong interaction between the roles and responsibilities of both actors.

From the business perspective, this thesis aims to apply and elaborate existing methods for business water footprint accounting and water footprint sustainability assessment, and to explore how the water footprint concept can form a basis for companies to extend their current corporate water strategies to the next steps to be taken: product transparency and water footprint reduction in the supply chain. The aim is to develop understanding of how a company can measure water consumption and improve water management across its operations and supply chain, with the final goal of building a sustainable water strategy.

With respect to the governmental perspective, the thesis explores whether the framework of water footprint and virtual water trade assessment can contribute to the identification of national water policy measures alternative or in addition to the traditional ones, which are limited to measures that focus either on increasing national water supply or on lowering water demand within the national territory by increasing water use efficiency.

1.5 Research questions

To guide this study the following research questions have been formulated:

(i) How can water footprint assessment be applied to business water accounting and how can companies benefit from the water footprint concept to build a wise corporate water strategy?

(ii) How can the water footprint concept be applied by national governments in formulating governmental policy that contributes to sustainable water use?

(iii) Can we learn from experiences with the use of the carbon footprint concept by business and governments in order to effectively use the water footprint concept? Are the sorts of policy instruments established for the carbon footprint applicable to the water footprint?

(iv) How can water footprint be addressed with other environmental footprints in a single analytical framework?

1.6 Structure of the thesis

This thesis starts with assessments from business perspective. Chapters 2 and 3 present two applications of WF for companies. The thesis continues with WF applications from governmental perspective. Chapter 4 shows an application of the WF at national level. Chapter 5 analysis how WF scenarios can inform national policy making in the long term. After governmental studies, the thesis explores to which extent we can draw lessons from the carbon footprint case in terms of adoption of policy responses for governments and companies (Chapter 6). It finishes with the assessment of how the WF can be used in combination with other environmental footprint indicators in a context of exploring the relation between economics and environmental pressure (Chapter 7).

Chapter 2 shows an application of water footprint accounting in business water accounting on product level. It analyses the water footprint of soymilk and soy burger products and compares them with their equivalent animal-based products (cow's milk and beef burgers). It starts with the assessment of the water footprint of soybean cultivation, differentiating between the green, blue and grey water components. Different types of soybean production systems are analysed: organic vs. non-organic and irrigated vs. rainfed. Next, the water footprint of the final products is assessed in relation to the composition of the product and the characteristics of the process and producing facility. Finally, it compares the water footprint of soy products with equivalent animal products.

The third chapter includes a pilot study on water footprint accounting and impact assessment for a hypothetical sugar-containing carbonated beverage. The water footprint of the beverage has been calculated by quantifying the water footprint of each input separately and by accounting for process water use as well. In addition, a local environmental impact assessment has been carried out, by looking at the occurrence of environmental problems in the regions where the water footprint of the product is located.

Chapter 4 carries out a water footprint assessment for France from both a production and consumption perspective. It analyses how French water resources are allocated over various purposes, and examines where the water footprint of production within France violates local environmental flow requirements and ambient water quality standards. In addition, it quantifies which volumes of French water resources are allocated for making products for export and to assess the impact related to this water footprint for export. It also includes the analysis of the external water footprint of French consumption, to get a complete picture of how national consumption translates to water use, not only in France, but also abroad. In this way we show French dependency on external water resources and the sustainability of imports.

Chapter 5 develops water footprint scenarios for 2050 based on a number of drivers of change: population growth, economic growth, production/trade pattern, consumption pattern (dietary change, bioenergy use), technological development. It goes beyond the previous global water scenario studies by a combination of factors: (i) it addresses blue and green water consumption instead of blue water withdrawal volumes; (ii) it considers water pollution in terms of grey water footprint; (iii) it analyses agricultural, domestic as well as industrial water consumption; (iv) it disaggregates consumption along major commodity groups; (v) it integrates all major critical drivers of change under a single, consistent framework. The water footprint scenarios consist of two assessments: one for the globe as a whole, distinguishing between 16 world regions, and another one for Europe, whereby we zoom in to the country level. Global study analyses the changes in the water footprint of production and consumption for possible futures by region and to elaborate the main drivers of this change. In addition, it assesses virtual water flows between the regions of the world to show dependencies of the regions on water resources in the other regions under different possible futures. In the European case study, we assess the water footprint of production and consumption at country level and Europe's dependence on water resources elsewhere in the world.

Chapter 6 analyses the origins and the characteristics of the carbon and water footprints in order to understand their similarities and differences and to derive lessons on how society and business can adequately build on the two concepts. The two concepts are compared from a methodological point of view. We discuss response mechanisms that have been developed, with the hope that experiences in one field might be able to benefit the other. We address the question whether policy responses that have been developed for the carbon footprint are applicable and suitable to the water footprint and investigate meaningful policy responses for the water footprint. Finally, we elaborate the role of governments and businesses in managing the footprints and formulating policy options.

Chapter 7 reflects on the role of water footprint in broader environmental policy development. It discusses the "footprint family" as a suite of indicators to track human pressure on the planet and under different angles. A description of the research question, rationale and methodology of the Ecological, Carbon and Water Footprint is first provided.

Similarities and differences among the three indicators are then highlighted to show how these indicators overlap and complement each other. It concludes by defining the “footprint family” of indicators and outlining its appropriate policy use at EU level.

The last chapter concludes the thesis by putting the main findings in the previous chapters into perspective.

2 The water footprint of soy milk and soy burger and equivalent animal products[1]

Abstract

As all human water use is ultimately linked to final consumption, it is interesting to know the specific water consumption and pollution behind various consumer goods, particularly for goods that are water-intensive, such as foodstuffs. The objective of this study is to quantify the water footprints of soy milk and soy burger and compare them with the water footprints of equivalent animal products (cow's milk and beef burger). The study focuses on the assessment of the water footprint of soy milk produced in a specific factory in Belgium and soy burger produced in another factory in the Netherlands. The ingredients used in the products are same as real products and taken from real case studies. We analysed organic and non-organic soybean farms in three different countries from where the soybeans are imported (Canada, China, and France). Organic production reduces soil evaporation and diminishes the grey water footprint, ultimately reducing the total water footprint. The water footprint of 1 litre soy milk is 297 litres, of which 99.7% refers to the supply chain. The water footprint of a 150 g soy burger is 158 litres, of which 99.9% refers to the supply chain. Although most companies focus on just their own operational performance, this study shows that it is important to consider the complete supply chain. The major part of the total water footprint stems from ingredients that are based on agricultural products. In the case of soy milk, 62% of the total water footprint is due to the soybean content in the product; in the case of soy burger, this is 74%. Thus, a detailed assessment of soybean cultivation is essential to understand the claim that each product makes on freshwater resources. This study shows that shifting from non-organic to organic farming can reduce the grey water footprint related to soybean cultivation by 98%.Cow's milk and beef burger have much larger water footprints than their soy equivalents. The global average water footprint of a 150 g beef burger is 2350 litres and the water footprint of 1 litre of cow's milk is 1050 litres.

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[1] Based on Ercin et al. (2012a)

2.1 Introduction

Given that severe freshwater scarcity is a common phenomenon in many regions of the world, improving the governance of the world's limited annual freshwater supply is a major challenge, not only relevant to water users and managers but also to final consumers, businesses and policymakers in a more general sense (UNESCO, 2006). About 86% of all water used in the world is to grow food (Hoekstra and Chapagain, 2008). Therefore, food choices can have a big impact on water demand (Steinfeld et al., 2006; De Fraiture et al., 2007; Peden et al., 2007; Galloway et al., 2007). In industrialised countries, an average meat-eater consumes the equivalent of about 3,600 litres of water a day, which is 1.6 times more than the 2,300 litres used daily by people on vegetarian diets (assuming the vegetarians still consume dairy products; Hoekstra, 2010).

Fresh water is a basic ingredient in the operations and supply chains of many companies. A company may face multiple risks related to failure in properly managing freshwater supplies: damage to its corporate image, the threat of increased regulatory control, financial risks caused by pollution, and inadequate freshwater availability for business operations (Rondinelli and Berry, 2000; Pegram et al., 2009). The need for the food industry to take a responsible approach towards the sustainable use and conservation of fresh water is therefore vital.

The 'water footprint' is an indicator of water use that looks at both direct and indirect water use by a consumer or producer (Hoekstra, 2003). The water footprint is a comprehensive indicator of freshwater resources appropriation, which goes beyond traditional restrictive measures of water withdrawal. The water footprint of a product is defined as the total volume of fresh water that is used directly or indirectly to produce the product. It is estimated by considering water consumption and pollution in all steps of the production chain. (Hoekstra et al., 2011). The blue water footprint refers to consumption of blue water resources (surface and ground water) along the supply chain of a product. 'Consumption' refers to the loss of water from the available ground and surface water in a given catchment area. It includes evaporatranspiration, water incorporated into products and return waters to another catchment area or the sea. The green water footprint refers to consumption of green water resources (rainwater). The grey water footprint refers to pollution and is defined as the volume of freshwater that is required to assimilate the load of pollutants based on existing ambient water quality standards.

This paper analyses the water footprints of soy milk and soy burger and compares them with the water footprints of two equivalent animal products (cow's milk and beef burger). For this purpose, we first identified the production-chain diagram of 1 litre of soy milk and of 150 g soy burger. We also indicated the relevant process steps with substantial water footprints. The study focuses on the assessment of the water footprint of soy milk produced in a specific factory in Belgium and soy burger produced in a specific factory in the Netherlands. The soybeans used in the manufacturing of the soy products in these two countries are imported. The study starts with the assessment of the water footprint of soybean cultivation in Canada, China and France, three of the actual source countries, differentiating between the green, blue and grey water footprint components. Different types of soybean production systems are analysed: organic versus non-organic and irrigated versus rain-fed. Next, the water footprint of each of the final products is assessed based on the composition of the product and the characteristics of the production process and producing facility. Finally, we compare the water footprints of soy products with the water footprints of equivalent animal products.

2.2 Method and data

In order to estimate the water footprint of soy milk and soy burger, first we identified production systems. A production system consists of sequential process steps. Figures 2.1 and 2.2 show the production system of soy milk and soy burger, respectively. These production diagrams show only the major process steps during the production and the inputs for each step that are most relevant for water footprint accounting. They do not show other steps in the life cycle of the products like transportation, elevation, distribution, end-use and disposal.

Taking the perspective of the producer of the soy milk and soy burger, the water footprints of the soy products include an operational and a supply-chain water footprint. The operational (or direct) water footprint is the volume of freshwater consumed or polluted in the operations of the producer of the soy products. It refers to the fresh water appropriated during the production of the soy products from their basic ingredients: water incorporated into the products, water evaporated during production processes and the volume of water polluted because of wastewater leaving the factory. The supply-chain (or indirect) water footprint is the volume of freshwater consumed or polluted to produce all the goods and services that form the input of production of the business. Both operational and supply-chain water footprints consist of two parts: the water footprint that can be directly related to inputs needed in or for the production of the product and an overhead water footprint. The overhead water footprint refers to freshwater use that in first instance cannot be fully associated with the production of the specific product considered, but refers to freshwater use that associates with supporting activities and materials used in the business, which produces not just this specific product but other products as well. The overhead components of the operational and supply-chain water footprints are excluded from this study as they are negligible compared to the total water footprint for food-based products (Ercin et al., 2011). Additionally, the water footprint related to transport of materials and energy used during production are excluded from this study as they are negligible compared to the total water footprint for food-based products (ibid.).

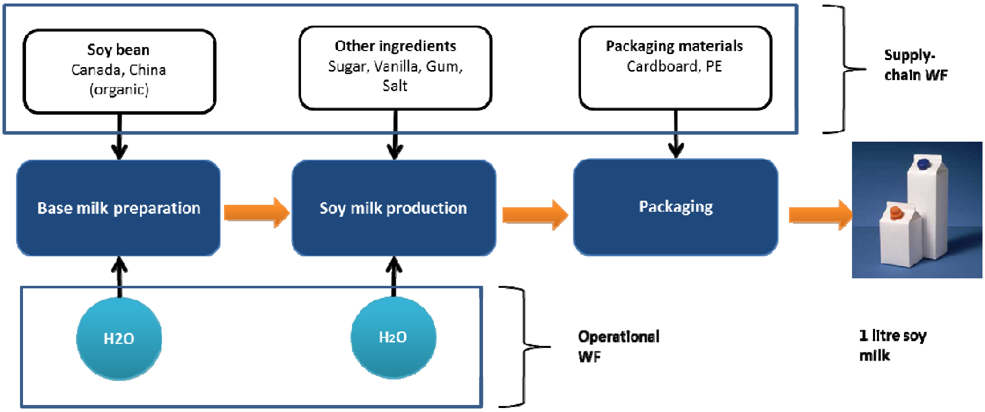

Figure 2.1. Production-chain diagram of soy milk produced in Belgium.

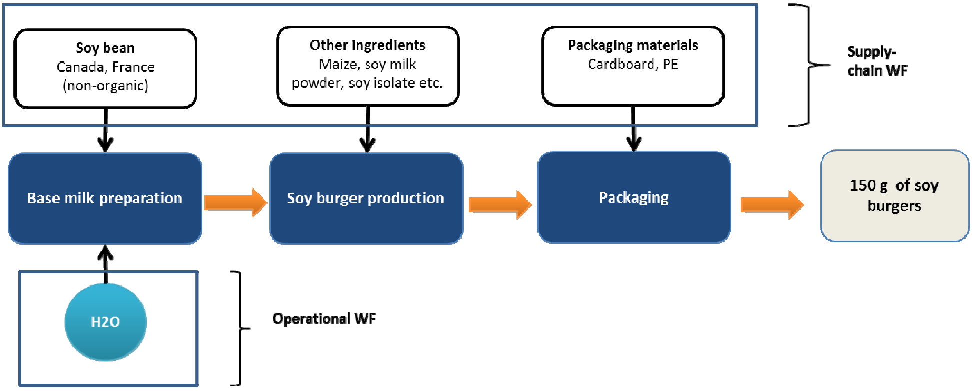

Figure 2.2. Production-chain diagram of a 150 g soy burger produced in the Netherlands.

The supply-chain water footprint is composed of the water footprints of ingredients (e.g. soybean, sugar, maize, and natural flavouring in the case of soy milk and soybean, maize, onion, paprika, carrots for soy burger) and the water footprints of other components (e.g. bottle, cap, labelling materials, packaging materials). The list of ingredients and amounts used in the soy products are taken from real case studies (Table 2.1 and 2.2). For the soy milk, the soybean is supplied from two different farms that cultivate organic soybean: a rainfed farm located in China and a rainfed farm located in Canada. In the production stage of the soy milk, a mix of soybeans from these two farms is used, according to a ratio of 50 to 50. For the soy burger, soybean is supplied from three non-organic farms: a rainfed farm located in Canada, a rainfed farm located in France, and an irrigated farm in the same region in France. A mix of soybeans from these farms is used in the soy burger, according to a ratio of 50/25/25.

Table 2.1. Water footprints of raw materials and process water footprints for the ingredients and other components of 1 litre soy milk.

1 litre of soy milk	Raw material	Amount* (g)	Source	Water footprint of raw material (m^3/ton)[a]			Process water footprint (m^3/ton)[b]			Fractions for products used[a]	
				Green	Blue	Grey	Green	Blue	Grey	Product fraction	Value fraction
Ingredients											
Soybean[c]	Soybean	70	Canada + China (organic)	1753.5	0	18.5	0	0	0	0.64	0.95
Cane sugar	Sugar cane	25	Cuba	358	50	2	0	0	0	0.11	0.87
Maize starch	Maize	0.30	China	565	12	335	0	0	0	0.75	1
Vanilla flavour	Vanilla	0.15	USA	67269	7790	0	0	0	0	9[d]	1
Other components											
Cardboard	Wood	25	Germany	616	0	0	0	0	180	1	1
Cap	Oil	2	Sweden (raw) - Germany (process)	0	0	10	0	0	225	1	1
Tray - cardboard	Wood	10	Germany	616	0	0	0	0	180	1	1
Stretch film (LDPE)	Oil	1.5	Sweden (raw) - Germany (process)	0	0	10	0	0	225	1	1

[a] Mekonnen and Hoekstra (2010a); Van Oel and Hoekstra (2010) for wood.

[b] Van der Leeden et al. (1990)

[c] Data for soybean: own calculations.

[d] FDA (2006)

*Total weight of ingredients is 0.1 kg. The rest of the weight is water, which is added in the operational phase.

Table 2.2. Water footprints of raw materials and process water footprints for the ingredients and other components of 150 g soy burger.

150 g of soy burger	Raw material	Amount* (g)	Source	Water footprint of raw material (m^3/ton)[a]			Process water footprint (m^3/ton)[b]			Fractions for products used[a]	
				Green	Blue	Grey	Green	Blue	Grey	Product fraction	Value fraction
Ingredients											
Soybean[c]	Soybean	25	France + Canada (non-organic)	1860	130	795	0	0	0	0.64	0.95
Maize	Maize	4	Turkey	646	208	277	0	0	0	1	1
Soy milk powder	Soybean	4	USA	1560	92	10	0	0	0	0.57	1
Soya paste	Soybean	4	USA	1560	92	10	0	0	0	3.75	1
Onions	Onions	4	Netherlands	68	5	18	0	0	0	1	1
Paprika green	Peppers green	5	Spain	39	3	37	0	0	0	1	1
Carrots	Carrots	2	Netherlands	57	3	18	0	0	0	1	1
Other components											
Sleeve (cardboard)	Wood	15	Germany	616	0	0	0	0	180	1	1
Plastic cup	Oil	15	Sweden (raw) - Germany (process)	0	0	10	0	0	225	1	1
Cardboard box (contains 6 burger packs)	Wood	25	Germany	616	0	0	0	0	180	1	1
Stretch film (LDPE)	Oil	0.5	Sweden (raw) - Germany (process)	0	0	10	0	0	225	1	1

[a] Mekonnen and Hoekstra (2010a); Van Oel and Hoekstra (2010) for wood.

[b] Van der Leeden et al. (1990)

[c] Data for soybean: own calculations.

*Total weight of ingredients is 0.05 kg. The rest of the weight is water, which is added in the operational phase.

The water footprints of different ingredients and other inputs are calculated distinguishing between the green, blue and grey water footprint components. The water footprint definitions and calculation methods applied follow Hoekstra et al. (2011). In order to calculate the water footprint of the soy products, we first calculated the water footprints of the original materials (raw materials) of the ingredients. The water footprint of agricultural raw materials (crops) is calculated as follows:

The green and blue component in water footprint of crops ($WF_{green/blue}$, m^3/ton) is calculated as the green and blue components in crop water use ($CWU_{green/blue}$, m^3/ha) divided by the crop yield (Y, ton/ha).

$$\mathrm{WFgreen/blue} = \frac{CWUgreen/blue}{Y} \qquad (2.1)$$

The green and blue water crop water use were calculated using the CROPWAT model (Allen et al., 1998; FAO, 2009a). Within the CROPWAT model, the ‘irrigation schedule option’ was applied, which includes dynamic soil water balance and tracks the soil moisture content over time (Allen et al., 1998). The calculations were done using climate data from the nearest and most representative meteorological stations and a specific cropping pattern for each crop according to the type of climate. Monthly values of major climatic parameters were obtained from the CLIMWAT database (FAO, 2009b). Crop area data were taken from Monfreda et al. (2008); crop parameters (crop coefficients, planting date and harvesting date) were taken from Allen et al. (1998) and FAO (2009a). Types of soil and average crop yield data were obtained from the farms (Table 2.3). Soil information was taken from FAO (2009a). All collected data are used as inputs for the CROPWAT model for calculation of crop water use.

In the case of the Chinese organic soybean production, organic compost mixed with the straw of the crop and the waste of livestock was applied. 50% of the soil surface was assumed to be covered by the organic crop residue mulch, with the soil evaporation being reduced by about 25% (Allen et al., 1998). For the crop coefficients in the different growth stages this means: Kc,ini, which represents mostly evaporation from soil, is reduced by about 25%; Kc,mid is reduced by 25% of the difference between the single crop coefficient (Kc,mid) and the basal crop coefficient (Kcb,mid); and Kc,end is similarly reduced by 25% of the difference between the single crop coefficient (Kc,end) and the basal crop coefficient (Kcb,end). Generally, the differences between the Kc and Kcb values are only 5-10%, so that the adjustment to Kc,mid and Kc,end to account for organic mulch may not be very large.

Table 2.3. Planting and harvesting dates, yield and type of soil for the five soybean farms considered.

Crop	Planting date*	Harvesting date*	Yield (ton/ha)*	Type of soil
Canada organic rainfed	15 May	11 October	2.4	Sandy loam - Clay loam
Canada non-organic rainfed	15 May	11 October	2.5	Clay loam
China organic rainfed	15 May	11 October	2.9	Brown soil
France non-organic rainfed	15 May	11 October	1.9	Calcareous clay
France non-organic irrigated	15 May	11 October	3.1	Calcareous clay

* Farm data

The grey water footprint of crops is calculated by dividing the pollutant load (L, in mass/time) by the difference between the ambient water quality standard for that pollutant (the maximum acceptable concentration cmax, in mass/volume) and its natural concentration in the receiving water body (cnat, in mass/volume).

$$WF_{proc,grey} = \frac{L}{c_{max} - c_{nat}} \qquad (2.2)$$

Table 2.4. Fertilizer and pesticide application and leaching rate and ambient water quality standards.

Type of agriculture	Chemical	Active substance	Application rate (kg/ha)	Leaching rate (%)	Leaching rate source	Standard (mg/l)	Standard source
Organic	Sulphate of potash	sulphate	25	60	Eriksen and Askegaard (2000)	300	MDEQ (1996) in MacDonald et al. (1999)
	Rock phosphate	phosphorus	11	0			
	Organic compost	nitrogen	1	10	Hoekstra and Chapagain (2008)	10	EPA (2010)
Non-organic	Potassium chloride	chloride	20	85	Stites and Kraft (2001)	860	EPA (2010) CMC - Criteria Maximum Concentration
	TSP	phosphorus	24	0			
	Touchdown	glyphosate	1	0.01	Dousset et al. (2004)	0.065	MDEQ (1996) in MacDonald et al. (1999)
	Boundary	metolachlor	2.4	1	Singh (2003)	0.008	MDEQ (1996) in MacDonald et al. (1999)
	Boundary	metribuzin	2.4	0	Kjaer et al. (2005)	0.001	MDEQ (1996) in MacDonald et al. (1999)
	P_2O_5	phosphorus	33	0			
	Lasso	alachlor	2	2.5	Persicani et al. (1995)	0.048	MDEQ (1996) in MacDonald et al. (1999)

Generally, soybean production leads to more than one form of pollution. The grey water footprint was estimated separately for each pollutant and finally determined by the pollutant that appeared to be most critical, i.e. the one that is associated with the largest pollutant-specific grey water footprint (if there is enough water to assimilate this pollutant, all other pollutants have been assimilated as well). The total volume of water required per ton of pollutant was calculated by considering the volume of pollutant leached (ton/ton) and the maximum allowable concentration in the ambient water system. The natural concentration of pollutants in the receiving water body was assumed to be negligible. Pollutant-specific leaching fractions and ambient water quality standards were taken from the literature (Table 2.4). In the case of phosphorus, good estimates on the fractions that reach the water bodies by leaching or runoff are very difficult to obtain. The problem for a substance like phosphorus (P) is that it partly accumulates in the soil, so that not all P that is not taken up by the plant immediately reaches the groundwater, but on the other hand may do so later. In this study we assumed a P leaching rate of zero.

Second step in calculation of water footprints of the soy products is the calculation of water footprints of each ingredient of the soy products. The water footprint of ingredient (p) is calculated as:

$$WF_{prod}\,[p] = \left(WF_{proc}\,[p] + \frac{WF_{prod}\,[i]}{f_p\,[p,i]}\right) \times f_v\,[p] \tag{2.3}$$

in which $WF_{prod}[p]$ is the water footprint of ingredient, $WF_{prod}[i]$ is the water footprint of raw material i and $WF_{proc}[p]$ the process water footprint. Parameter $f_p[p,i]$ is the 'product fraction' and parameter $f_v[p]$ is the 'value fraction'. The product fraction of ingredient p that is processed from raw material i ($f_p[p,i]$, mass/mass) is defined as the quantity of the ingredient (w[p], mass) obtained per quantity of raw material (w[i], mass):

$$f_p[p,i] = \frac{w[p]}{w[i]} \tag{2.4}$$

The value fraction of ingredient p (fv[p], monetary unit/monetary unit) is defined as the ratio of the market value of this ingredient to the aggregated market value of all the outputs products (p=1 to z) obtained from the raw material:

$$f_v[p] = \frac{price[p] \times w[p]}{\sum\limits_{p=1}^{z} \left(price[p] \times w[p]\right)} \tag{2.5}$$

The water footprint of the soy products is then sum of water footprint of all ingredients (p=1 to y) multiplied with the amounts of ingredients (Mp) used in the products:

$$WF_{soyproducts} = \sum_{p=1}^{y} WF_p \text{ x} M_p \tag{2.6}$$

As an example to water footprint calculation of the ingredients, we show here the case of soybean used in 150 g of soy burger. The amount of soybean used in the soy burger is 0.025 kg and is cultivated in Canada and France (50% each). The green, blue and grey water footprints of the soybean mix are 1860, 130 and 795 m^3/ton, respectively. About 86% of the weight of soybean becomes dehulled soybean (DS) and about 74% of the DS weight becomes base milk. The product fraction for soybean in the product (basemilk) is thus 0.86 × 0.74 = 0.64. In the process from soybean to basemilk, there are also by-products with some value. The value of the basemilk is 94% of the aggregated value of soybean products. Therefore, 94% of the water footprint of the soybean is attributed to basemilk. The water footprint of the basemilk as used in the soy milk is calculated by multiplying the water footprint of soybean by the value fraction and amount used and dividing by the product fraction. The green water footprint of the basemilk is thus: (1860×0.94×0.025)/0.64 = 69.1 litres. The blue water footprint: (130×0.94×0.025)/0.64 = 4.8 litres. The grey water footprint: (795×0.94×0.025)/0.64 = 29.5 litres.

For the other agricultural ingredients, water footprints of raw products, product fractions and value fractions have been taken from Mekonnen and Hoekstra (2010a). We calculated the product and value fractions of the vanilla extract according to the extracting process defined as in FDA (2006). In this calculation, we assumed that single fold vanilla extract is used in the soy milk. The water footprints of raw materials, process water footprints, product fractions and value fractions, on which the soy milk and soy burger water footprint's calculation is based, are given in Table 2.1 and 2.2.

The supply-chain water footprint of soy products is not only caused by ingredients but also other components integral to the whole product. These include closure, labelling and packaging materials. The process water footprints and the water footprints associated with other raw materials used (oil, PE, LDPE, PP) have been derived from Van der Leeden et al. (1990). The detailed list of other components of the supply-chain water footprint of the product is given in Table 2.1 and 2.2. The water footprints of raw materials, process water footprints, product fractions and value fraction are presented in Table 2.1 and 2.2.

Data related to the operational water footprint of soy milk and soy burger are taken from two real factories in Belgium and the Netherlands. Both factories have treatment plants that treat the wastewater before discharging it into the receiving water bodies. All wastewater leaving the factories is treated with 100% treatment performance at both treatment plants and effluent characteristics of the treated wastewater are below the legal limits. Therefore, we took the grey water footprint as zero by assuming that the concentration of the pollutant in the effluent is equal to its actual concentration in the receiving water body.

The water used as an ingredient is equal to 0.1 litres per 150 g of soy burger and 0.9 litres per 1 litre of soy milk. The production of soy milk and soy burger includes the following process steps: base milk preparation, mixing, filling, labelling and packaging. The water balance recordings of the factories showed that the amount of water lost (evaporated) is zero during all these processes. Base milk in the production process refers to the preparation of concentrated milk.

The water footprints of cow's milk and beef depend on the water footprints of the feed ingredients consumed by the animal during its lifetime and the water footprints related to drinking and service water (Hoekstra and Chapagain, 2008). Clearly, one needs to know the age of the animal when slaughtered and the diet of the animal during the various stages of its life. The water footprints of cow's milk and beef burger have been taken from Mekonnen and Hoekstra (2010b). For the comparison with the soy products, the water footprint of packaging is included in the water footprints of cow's milk and beef burger as well.

2.3 Results

2.3.1 Water footprint of soybean

The water footprints of soybean cultivated in five different farms located in three different countries are shown in Figure 2.3. The soybean from the Canadian non-organic farm has the largest water footprint, followed by the two French non-organic farms, the Canadian organic farm and Chinese organic farm. The blue water footprint component is zero except for the soybean from the French irrigated farm. The soybean from the rest of the farms is rainfed. The largest grey water footprint is found for the soybean from the Canadian non–organic farm.

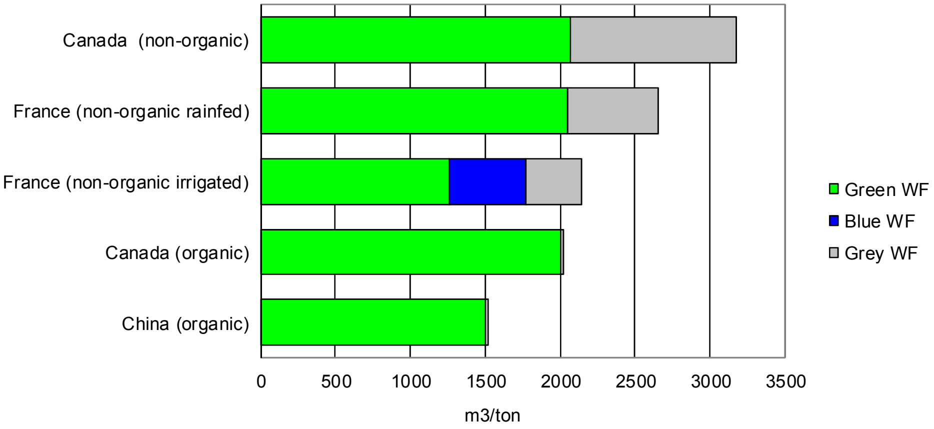

Figure 2.3. The water footprint of soybeans (as primary crops) from different farms (m^3/ton).

Soybean cultivation in Canada

In Canada, two different plantations were analysed: a rainfed organic and a rainfed non-organic soybean farm. As reported in Table 2.3, crop yields for the organic and non-organic soybean production in the Canadian farms are similar (2.4 and 2.5 ton/ha, respectively). The water footprint of non-organic soybean production is about 3172 m^3/ton (2069 m^3/ton green and 1103 m^3/ton grey) (Figure 2.3). The grey water footprint is determined by Boundary herbicide, which has the largest pollutant-specific grey water footprint (1103 m^3/ton), followed by potassium chloride (8 m^3/ton), Touchdown (1 m^3/ton) and TSP (0 m^3/ton). The total water footprint of organic soybean production in the Canadian farm is around 2024 m^3/ton (2004 m^3/ton green, 20 m^3/ton grey). In this case, the sulphate of potash is the most critical pollutant (20 m^3/ton). The nitrogen fertilization through symbiotic and endophytic bacteria as applied in organic farming has a zero grey water footprint.

Soybean cultivation in China

The Chinese organic rainfed farm under study achieves high yields, amounting to about 2.9 ton/ha, notably higher than the Chinese national average (1.7 ton/ha). The total water footprint of the Chinese organic rainfed soybean production is 1520 m^3/ton (1503 m^3/ton green and 17 m^3/ton grey). The grey water footprint is related to the sulphate pollution coming from the sulphate of potash applied. The grey water footprint of nitrogen due to organic compost is 4 m^3/ton and the one of phosphorus (P2O5) is negligible. In this case, organic compost mixed by the straw of the crop and the waste of the livestock is applied, mainly before planting.

Soybean cultivation in France

The non-organic rainfed French farm studied has a low yield of around 1.9 ton/ha, whereas the irrigated one gives 3.1 ton/ha, higher than the national average (2.5 ton/ha). The water footprint of the soybean from the rainfed farm is calculated as 2651 m^3/ton (2048 m^3/ton green and 603 m^3/ton grey). The water footprint for the irrigated farm is estimated as 2145 m^3/ton (1255 m^3/ton green, 519 m3/ton blue and 370 m^3/ton grey). In both cases, the grey water footprint is determined by the Lasso pesticide (alachlor) applied (603 and 370 m^3/ton for rainfed and irrigated production, respectively), followed by the potassium chloride pollution (10 and 6 m^3/ton respectively) and TSP (0 m^3/ton).

2.3.2 Water footprint of soy products

The operational water footprints of soy milk and soy burger are very small (Tables 2.5 and 2.6). Both green and grey water footprints are zero. The blue water footprint is 0.9 litre of water for soy milk and 0.1 litres for soy burger. The total operational water footprint is thus no more than the water used as ingredient of the products.

The water footprints of the two soy products are largely determined by the supply chain components. About 62% of the total water footprint of soy milk refers to the water footprint of soybean cultivation. In the case of soy burger, this is 65%. In the case of soy milk, 90% of the supply-chain water footprint is from ingredients (mainly soybean and cane sugar) and 10% is from other components (mainly cardboard). For soy burger, the percentages are 78% and 22% respectively.

Table 2.5. The water footprint of 1 litre of soy milk.

	Water footprint (litres)				
	Green	Blue	Grey	Total	% in total
Water incorporated into the soy milk	0	0.9	0	0.9	0.3
Water consumed during process	0	0	0	0	0
Wastewater discharge	0	0	0	0	0
Operational water footprint	**0**	**0.9**	**0**	**0.9**	**0.3**
Soybean (basemilk)	182.3	0	1.9	184.2	62
Cane sugar	71.1	9.9	0.4	81.5	27.5
Maize starch	0.2	0	0.1	0.4	0.1
Vanilla flavour	1.1	0.1	0	1.3	0.4
Ingredients total	**254.7**	**10**	**2.4**	**267.4**	**90**
Cardboard	15.4	0.0	4.5	19.9	6.7
Cap	0.0	0.0	0.5	0.5	0.2
Tray - cardboard	6.2	0.0	1.8	8.0	2.7
Stretch film (LDPE)	0.0	0.0	0.4	0.4	0.1
Other components total	**21.6**	**0**	**7.2**	**28.8**	**9.7**
Supply-chain water footprint	**276.4**	**10.1**	**9.6**	**296**	**99.7**
Total	**276.4**	**11.0**	**9.6**	**296.9**	

The results in Tables 2.5 and 2.6 are calculated based on the figures given in Table 2.1 and 2.2. As an example, we show here the calculation of the water footprint of soybean used in 150 g of soy burger. The amount of soybean used in the soy burger is 0.025 kg and is cultivated in Canada and France (50% each). All soybeans come from non-organic farms. In France, the soybean come partly from rainfed lands and partly from irrigated lands. The

Canadian soybean is taken from rainfed fields. The water footprints of soybeans as primary crop from different locations are given in Table 2.7. The green, blue and grey water footprints of soybean from Canada are 2069, 0 and 1103 m^3/ton, respectively. For rainfed soybean from France this is 2048, 0, and 603 m^3/ton, respectively. For irrigated French soybean, we find values of 1255, 519 and 370 m^3/ton. Based on relative amounts per source, we can calculate that the green, blue and grey water footprints of the resulting soybean mix are 1860, 130 and 795 m^3/ton, respectively.

Table 2.6. The water footprint of 150 g of soy burger.

	Water footprint (litres)				
	Green	Blue	Grey	Total	% in total
Water incorporated into the soy milk	0	0.1	0	0.1	0.06
Water consumed during process	0	0	0	0	0
Wastewater discharge	0	0	0	0	0
Operational water footprint	**0**	**0.1**	**0**	**0.1**	**0.06**
Soybean (basemilk)	69.1	4.8	29.5	103.4	65.5
Maize	2.6	0.8	1.1	4.5	2.8
Soy milk powder	10.9	0.6	0.1	11.7	7.4
Soya paste	1.7	0.1	0.0	1.8	1.1
Onions	0.3	0	0.1	0.4	0.3
Paprika green	0.2	0	0.2	0.4	0.3
Carrots	0.1	0	0	0.2	0.1
Ingredients total	**84.9**	**6.3**	**31**	**122.4**	**77.5**
Sleeve (cardboard)	9.2	0	2.7	11.9	7.5
Plastic cup	0.0	0	3.5	3.5	2.2
Cardboard box (contains 6 burger packs)	15.4	0	4.5	19.9	2.6
Stretch film (LDPE)	0	0	0.1	0.1	0.06
Other components total	**24.6**	**0**	**10.8**	**35.4**	**22.36**
Supply-chain water footprint	**109.5**	**6.4**	**41.8**	**157.8**	**99.9**
Total	**109.5**	**6.5**	**41.8**	**157.9**	

The total water footprints of 1 litre of soy milk and 150 g of soy burger are calculated as 297 and 158 litres respectively. For soy milk, 99.7% of total water footprint stems from the supply-chain water footprint. For soy burger this is 99.9%. This highlights the importance of detailed supply chain assessments for both products and businesses. Common practice in business water accounting is the focus on the operational water consumption. However, this study shows that compared to the supply-chain water footprint, the operational side is almost negligible. The diagrams in Figure 2.4 show the colour composition of the water footprints of soy milk and soy burger. 93% of the total water footprint of the 1 litre of soy milk is from green water resources, 4% is from blue water resources and 3% is the grey water footprint component. The colours of the water footprint of 150 g soy burger are 69% green, 4% blue and 27% the grey.

Table 2.7. Summary of the water footprints of soybeans as primary crop (as input to a soy burger).

Farm	Water footprint (m^3/ton)				Percentage in mix
	Green	Blue	Grey	Total	
Canada (non-organic, rainfed)	2069	0	1103	3172	50
France (non-organic, rainfed)	2048	0	603	2651	25
France (non-organic, irrigated)	1255	519	370	2145	25
Soybean mix (for soy burger)	1860	130	795	1860	

The water footprints of soy milk and soy burger from the Belgian and Dutch factories are calculated based on the percentages of soybean intake from different farms. Figure 2.5 shows the change in the total footprint of 1 litre of soy milk according to farm location and type of agricultural practice (organic vs. non-organic and rainfed vs. irrigated). The soybean used as an ingredient in the ‘soy milk product’ is supplied from both Canadian and Chinese organic farms (50% each). Figure 2.5 shows the total water footprint values of the same product when soybeans are fully supplied from either the Canadian organic, Chinese organic, French non-organic rainfed, French non-organic irrigated, or Canadian non-organic farm. If the soybean were only supplied from the Canadian non-organic farm, the water footprint of 1 litre of soy milk would be 49% larger. If all soybeans were supplied from the Chinese organic farm, then the water footprint of the soy milk product would be 9% smaller. Shifting from full non-organic (as in the one Canadian farm) to full organic (as in the other Canadian farm) reduces the grey water footprint related to soybean cultivation by 98%.

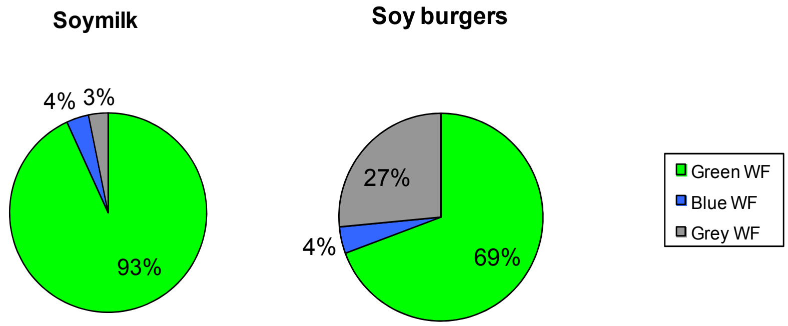

Figure 2.4. The green, blue and grey shares in the total water footprints of 1 litre soy milk and 150 g soy burger.

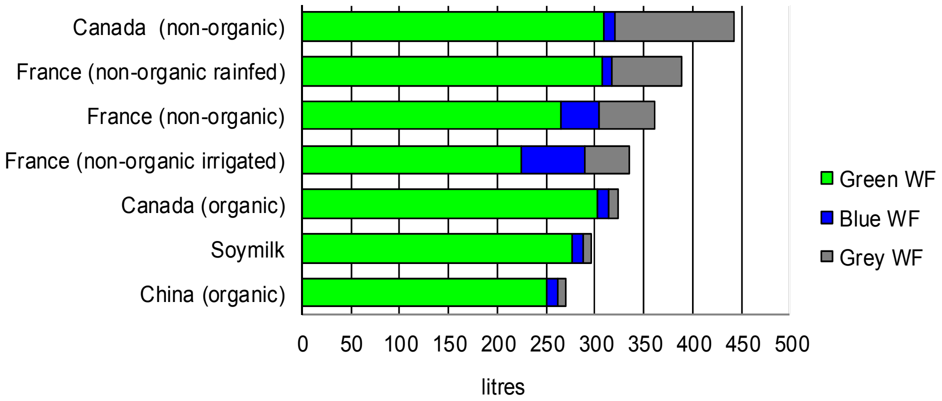

Figure 2.5. The total water footprint of soy milk with soybean input from different farms (litres).

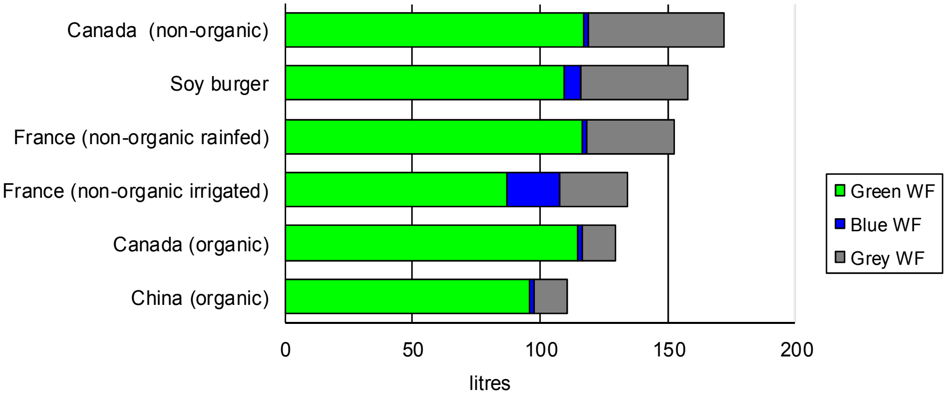

Figure 2.6. The total water footprint of soy burger with soybean input from different farms (litres).

The soybean in the 150 g of soy burger is supplied from three different farms: a non-organic Canadian farm (supplying 50% of the soybean) and two non-organic French farms, a rainfed one and an irrigated one (both supplying 25%). The total water footprint of this soy burger is 158 litres (Figure 2.6). If we were to source soybean only from the Canadian non-organic farm, the total water footprint of our product would be 9% higher. However, if we sourced soybean from the Chinese organic farm that we studied for the soy milk case, the total water footprint of our soy burger would decrease by 30%.

2.3.3 Water footprint of soy products versus equivalent animal products

The water footprints of cow's milk and beef burger have been studied in detail before by Chapagain and Hoekstra (2004) and recently by Mekonnen and Hoekstra (2010b). In this study we make use of the estimates from the latter study. In the latter study packing is not included in the water footprint values. Therefore, for the comparison of cow's milk and soy milk, the water footprint of packaging material is added to the water footprint of cow's milk (27.8 litres per 1 litre of milk). Similarly, the water footprint of packaging materials is added to the beef burger for fair comparison with the soy burger (35.5 litres per 150 g of beef burger). The packing for animal products are taken as same as the soybean products.

Figure 2.7 shows the water footprint of 1 litre of soy milk produced in Belgium in comparison to the water footprint of 1 litre of cow's milk from various locations. The smallest water footprint of cow's milk is 540 litres for the UK and the largest is 1800 litres for Spain, while the world average amounts to 1050 litres.

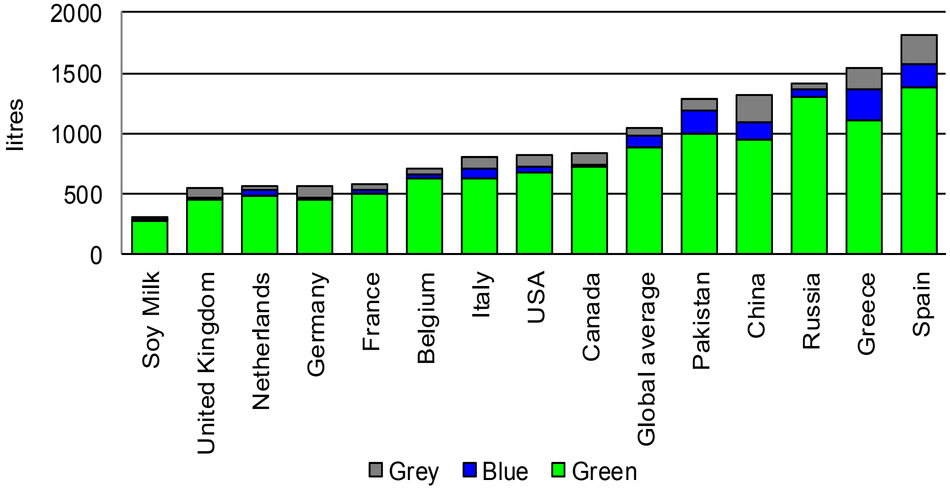

Figure 2.7. The water footprint of 1 litre of soy milk compared to the water footprint of 1 litre of cow's milk from various locations (in litres).

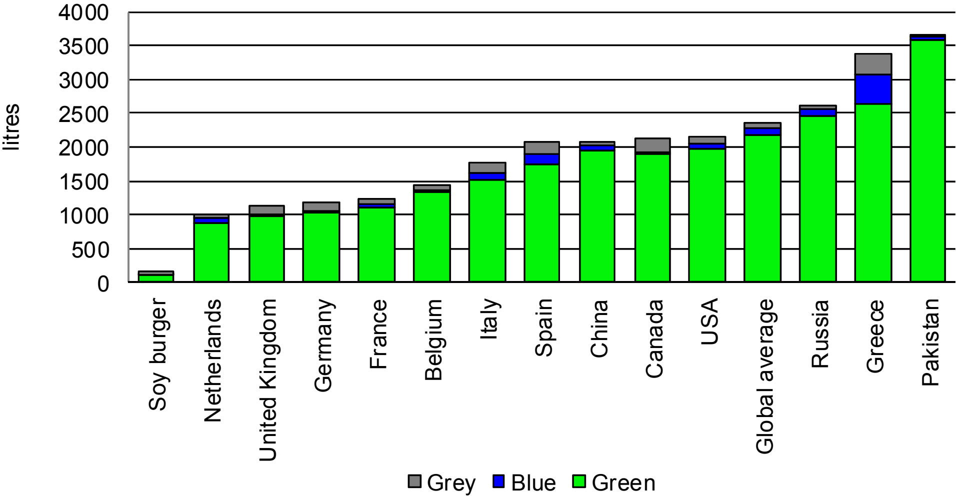

Figure 2.8. The water footprint of 150 g of soy burger compared to the water footprint of 150 g of beef burger from various locations (in litres).

Figure 2.8 compares the water footprint of 150 g of soy burger produced in the Netherlands with the water footprints of beef burgers from different locations. As seen in the figure, soy burger has a smaller water footprint (158 litres) than all the beef burgers from any source. The largest water footprint of beef burger is from Pakistan (3650 litres) and the lowest is from the Netherlands (1000 litres), while the world average is 2350 litres. The water footprint values change by location as the climatic, soil conditions and production systems varies across the countries.

2.4 Discussions

The calculations in this study are based on some assumptions. First, we assumed that the concentration of the pollutant in the effluent is equal to its actual concentration in the receiving water body during the production of the products. Therefore, the operational grey water footprint becomes zero. We introduce this assumption as the wastewater treatment levels in the Netherlands and Belgium are very high and the regulations for treatment of industrial wastewater are very strict. Additionally, this assumption has a very little effect on the total water footprint of the products (less than 1%). Second assumption is that there is no water loss in the production processes. The water balance recordings of the factories indicate that water intake is almost equal to the wastewater discharge from the factories. Therefore, our assumption is very close to the real case. Another assumption is that vanilla extract used in the products is single folded. It might be the case that vanilla extract is multi folded; however the effect of this to the total water footprint of soy burger is negligible.

This study only focuses accounting phase of water footprint assessment and excludes impact assessments. For a more in-depth analysis of the local environmental and social impacts of water footprints of products, one would have to analyse the water footprints in their geographic context, considering for example local water scarcity and pollution and effects on local ecosystems and social conflict. In the current study, this has not been done because the interest was not to study local impacts, but to compare the claims on freshwater resources of soy products versus equivalent animal products and to consider how the type of agricultural practice (organic versus non-organic; rainfed versus irrigated) can influence freshwater claims as well. Additionally we did not assess and take the environmental damages due to extensive soybeans production into consideration. Some possible damages can be deforestation, land degradation and soil pollution (WWF, 2003). Our analysis also does not reflect the human needs for nutrients such as proteins, calcium. It may be the case that more soy-product is required to fully match the nutrients that is taken from animal products.

The case of French farms is a good example of how irrigation can affect the water footprint value. The two French farms are located in the same region with similar climatic conditions. However, the first farm irrigates its field to obtain higher yields and the second farm cultivates soybean only with rainwater. The comparison of the water footprints shows that soybeans from the irrigated farm have a smaller total water footprint (14%), but the irrigated soybeans have a five times larger *blue* water footprint and a larger *grey* water footprint as well. This result is important, as generally competition over blue water resources is larger (i.e. they are scarcer), so that it may well be that from both an economic and environmental point of view the benefit of the reduced blue and grey water footprints in rainfed farming exceeds the cost of the increased green water footprint. Obviously, the analysis presented here is a partial one, focussed on showing green and blue water consumption and pollution; for a complete assessment of rainfed versus irrigated farming one needs to take other relevant factors into account as well, like the costs of both practices and the scarcity of (i.e. the competition over) both the green and blue water resources.

In the example of soy bean cultivation in France, there is space for improving rainfed soybean yields and therefore reducing the water footprint. This could be done in number of ways, for example by selecting high-yielding, well-adapted varieties, controlling weeds prior to planting, planting at the optimum seeding rates, depth and timing, harvesting at the optimum stage and adjusting combine settings (Staton et al., 2010). The grey water footprint could also be reduced by shifting to integrated or organic farming systems.

Organic farmers grow crops without using synthetic pesticides or fertilizers, relying instead on a wide range of cultural practices and alternative inputs believed to be safer for the environment and the consumer. Soybeans are relatively easy to produce using organic methods. However, it is important to recognize that organic farms rarely focus on a single crop. Organic soybean is grown in rotation with several other crops that (ideally) complement or compensate for one another. Crop rotations serve two primary purposes: to improve soil fertility and to break pest cycles. With regard to fertility management, rotation strategies concentrate mainly on generating and conserving nitrogen. Nitrogen is commonly the most limiting element in organic production, especially for corn and small grains, which complement soybeans in most crop sequences. Crop rotations that include forage legumes are the key where nitrogen is supplied to the system (NCAT, 2004). Organic production has slightly lower water consumption because the evapotranspiration from the field is less (Allen et al., 1998) and results in much less pollution because the load of chemicals to groundwater and surface water is less. Organic production systems also have other environmental benefits beside grey and blue water footprint reductions. Organic agricultural production systems also have lower ecological footprints (Niccolucci et al., 2008).

The current study is not based on field measurements of water consumption and leaching of applied chemicals, but based on statistics supplied by the farms and simple models to estimate evapotranspiration and water pollution. The figures presented should therefore be considered as very rough first estimates only.

2.5 Conclusions

This study shows the importance of a detailed supply-chain assessment in water footprint accounting. Food processing industries commonly consider water use in their own operations only. If they have water use reduction targets, those targets are formulated with regard to their own water use. With examples for two soybean products, this study shows that, however, the operational water footprint is almost negligible compared to the supply-chain water footprint. For a food processing company, it is crucial to recognize farmers as key players if the aim is to reduce the overall water consumption and pollution behind final food products. Engaging with farmers and providing positive incentives for the adoption of better agricultural practices are an essential element in a food company's effort to make its products sustainable.

The results of the study show that the water footprint of a soy product is very sensitive to where the inputs of production are sourced from and under which conditions the inputs are produced. This is most in particular relevant for the agricultural inputs. The water footprints of soy milk and soy burger depend significantly on the locations of the farms producing the soybean and on the agricultural practices at these farms (organic vs. non-organic and rainfed vs. irrigated). Not only the total water footprint, but also the colour composition (the ratios green, blue, and grey) strongly varies as a function of production location and agricultural practice. These results reveal the importance of the spatial dimension of water accounting.

For the limited number of cases that we have considered, we find that non-organic soybean has a larger water footprint (ranging between 2145-3172 m^3/ton) than organic soybean (1520-2024 m^3/ton). Organic agriculture, apart from having a lower evapotranspiration, reduces the grey water component. Shifting towards organic production will reduce the grey water footprint of agricultural production and thus the damage to aquatic life and ecosystems. Another factor that can be influenced is the degree of irrigation. In the case of the two French farms considered in this study, the total water footprint is larger for rainfed soybean, but the blue water footprint of rainfed soybean is zero.

The study shows that soy milk and soy burger have much smaller water footprints than their equivalent animal products. The water footprint of the soy milk product analysed in this study is 28% of the water footprint of the global average cow milk. The water footprint of the soy burger examined here is 7% of the water footprint of the average beef burger in the world.

3 Corporate water footprint accounting and impact assessment: The case of the water footprint of a sugar-containing carbonated beverage[2]

Abstract

All water use in the world is ultimately linked to final consumption by consumers. It is therefore interesting to know the specific water requirements of various consumer goods, particularly the water-intensive ones. This information is relevant not only for consumers, but also for food processors, retailers, and traders. The objective of this paper is to carry out a pilot study on water footprint accounting and impact assessment for a hypothetical sugar-containing carbonated beverage in a 0.5 litre PET-bottle produced in a hypothetical factory that takes its sugar alternatively from sugar beet, sugar cane and high fructose maize syrup and from different countries. The composition of the beverage and the characteristics of the factory are hypothetical but realistic. The data assumed have been inspired by a real case. This paper does not only look at the water footprint of the ingredients of the beverage, but also at the water footprint of the bottle, other packaging materials and construction materials, paper and energy used in the factory. Although most companies focus on their own operational performance, this paper shows that it is important to consider freshwater usage along the supply chain. The water footprint of the beverage studied has a water footprint of 150 to 300 litres of water per 0.5 litre bottle, of which 99.7-99.8% refers to the supply chain. The study also shows that agricultural ingredients that constitute only a small fraction in weight of the final product have the biggest share at the total water footprint of a product.

3.1 Introduction

Freshwater in sufficient quantities and adequate quality is a prerequisite for human societies and natural ecosystems (Costanza and Daly, 2002). Today, around 70% of the total freshwater withdrawal by humans is for irrigated agricultural use (Gleick, 1993; Bruinsma,

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[2] Based on Ercin et al. (2011)

2003; Shiklomanov and Rodda, 2003; UNESCO, 2006). Agriculture as a whole is responsible for about 86% of the worldwide freshwater use (Hoekstra and Chapagain, 2007). Agriculture has to compete with other water users like municipalities and industries (Rosegrant and Ringler, 1998; UNESCO, 2006). Freshwater is a basic ingredient for many companies' operations, and effluents may pollute the local hydrological ecosystems. Many companies have addressed these issues and formulated proactive management strategies (Gerbens-Leenes *et al.*, 2003). A company may face four serious risks related to failure to manage the freshwater issue: damage to the corporate image, the threat of increased regulatory control, financial risks caused by pollution and insufficient freshwater availability for business operations (Rondinelli and Berry, 2000; WWF, 2007).

The water footprint is an indicator of water use that looks at both direct and indirect water use of a consumer or producer. The water footprint of an individual, community or business is defined as the total volume of freshwater that is used to produce the goods and services consumed by the individual or community or produced by the business (Hoekstra and Chapagain, 2008). Water use is measured in terms of water volumes consumed (evaporated or incorporated into the product) and polluted per unit of time. The water footprint is a geographically explicit indicator, not only showing volumes of water use and pollution, but also the locations. Compared to other water accounting tools, water footprint provides the most extended and complete water accounting method, since it includes both direct and indirect water use and considers both water consumption and pollution. It has already been applied for various purposes, such as the calculation of the water footprint of a large number of products from all over the world (Chapagain and Hoekstra, 2004), but so far there have been few applications for business accounting.

The objective of this paper is to carry out a pilot study on water footprint accounting and impact assessment for a hypothetical sugar-containing carbonated beverage in a 0.5 litre PET-bottle produced in a hypothetical factory that takes its sugar alternatively from sugar beet, sugar cane and HFMS (high fructose maize syrup) sourced from different countries. The aim is primarily to learn from the practical use of existing water footprint accounting and impact assessment methods and to refine these methods and develop practical guidelines. The whole assessment has been inspired by a real case. From a scientific point of view, this paper aims to assess the necessary scope of analysis and, in particular, to explore the degree of detail required in such a study. Finally, an impact assessment of the water footprints is carried out, identifying the hotspots or high-risk areas.

3.2 Method

This study estimates the water footprint of a hypothetical 0.5 litre PET-bottle sugar-containing carbonated beverage. It looks into more detail at the water footprint of the sugar input, by considering three different sources (sugar beet, sugar cane and HFMS) and various countries of origin. The water footprint of different ingredients and other inputs is calculated distinguishing the green, blue and grey water components. The green water footprint refers to the global green water resources (rainwater) consumed to produce the goods and services. The blue water footprint refers to the global blue water resources (surface water and ground water) consumed to produce the goods and services. ‘Consumption’ refers here to ‘evaporation’ or ‘incorporation into the product’. It does not include water that is withdrawn but returns to the system from where it was withdrawn. The grey water footprint is the volume of polluted water that associates with the production of goods and services. The calculation methods applied in this study follow Hoekstra *et al.* (2009).

The total water footprint of a business contains various components as shown in Figure 3.1. The ‘business’ considered in this paper refers to the part of the factory that produces our 0.5 litre PET bottle sugar-containing carbonated beverage. The factory produces also other products, but this falls outside the scope of this paper. The water footprint of our product includes both an operational water footprint and a supply-chain water footprint. The operational (or direct) water footprint is the volume of freshwater consumed or polluted in the operations of the business itself. The supply-chain (or indirect) water footprint is the volume of freshwater consumed or polluted to produce all the goods and services that form the input of production of the business. Both operational and supply-chain water footprint consist of two parts: the water footprint that can be directly related to inputs applied in or for the production of our product and an overhead water footprint. In both cases, we distinguish between a green, blue and grey water footprint.

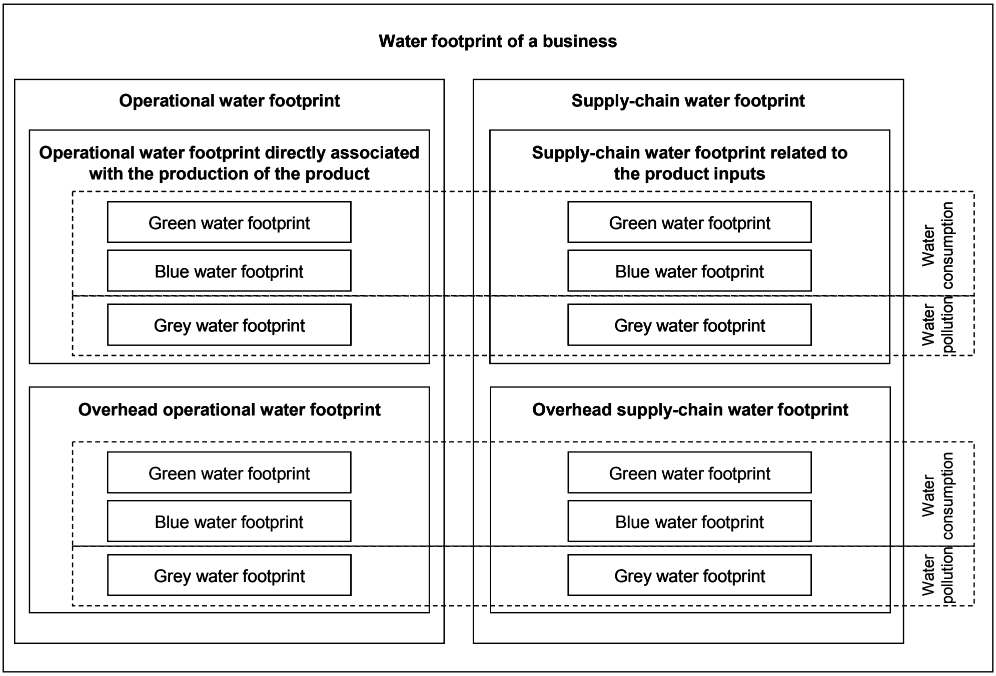

Figure 3.1. Composition of the water footprint of a business.

Figure 3.2 shows the production system of our product. It shows the four main ingredients of the beverage (water, sugar, CO_2 and syrup for flavouring) and the other main inputs of production (bottle, cap, label and glue, packing materials).

The production system shown in Figure 3.2 does not show the overhead of production. The overhead of production refers to all inputs used that cannot be solely attributed to the production of the specific product considered. The overhead water footprint refers to freshwater use that in first instance cannot be fully associated with the production of the specific product considered, but refers to freshwater use that associates with supporting activities and materials used in the business, which produces not just this specific product but other products as well. The overhead water footprint of a business has to be distributed over the various business products, which is done based on the relative value per product. The overhead water footprint includes, for example, the freshwater use in the toilets and kitchen of a factory and the freshwater use behind the concrete and steel used in the factory and machineries.

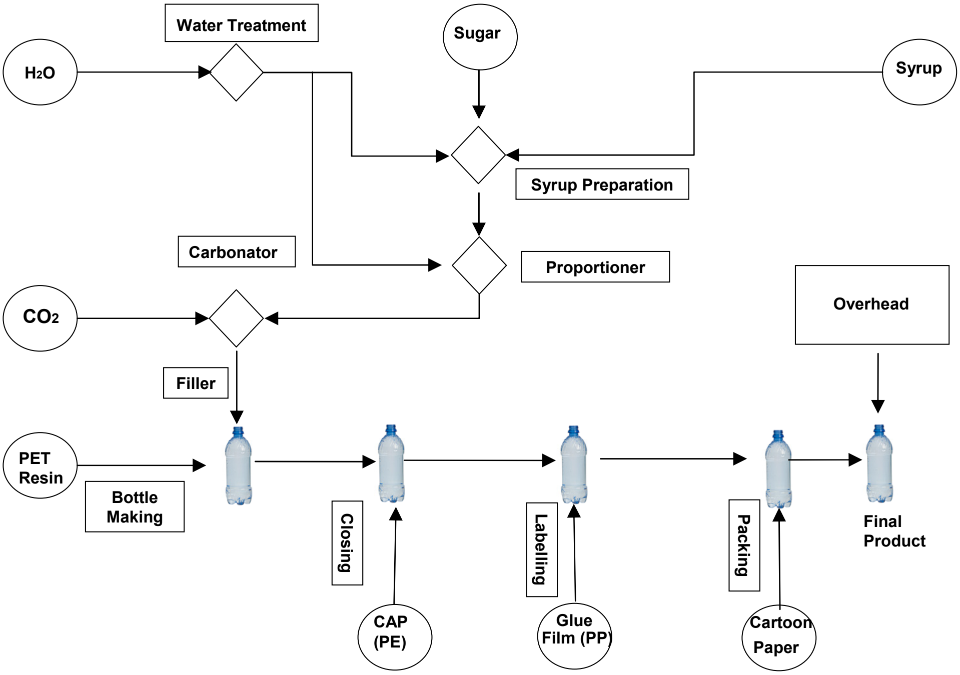

Figure 3.2. Production system of the 0.5 litre PET-bottle sugar-containing carbonated beverage.

3.3 Data sources and assumptions

For the assessment, we have formulated a hypothetical sugar-containing carbonated beverage in a 0.5 litre PET-bottle and a hypothetical factory that takes its sugar alternatively from sugar beet, sugar cane and HFMS (high fructose maize syrup) sourced from different countries. The factory itself is assumed to be in the Netherlands, but many of the inputs come from other countries. The composition of the beverage and the characteristics of the factory are hypothetical but realistic. The set of data assumed has been inspired by a real case.

3.3.1 Operational water footprint

Operational water footprint directly associated with the production of the product

The following components are defined as operational water footprint:

- Water incorporated into the product as an ingredient.
- Water consumed (i.e. not returned to the water system from where it was withdrawn) during the production process (during bottling process, washing, cleaning, filling, labelling and packing).
- Water polluted as a result of the production process.

The first two components form the blue operational water footprint; the third component forms the operational grey water footprint. There is no use of green water (rainwater) in the operations, so there is no operational green water footprint.

The water used as ingredient is 0.5 litres per bottle. The production of our beverage includes the following process steps: bottle making (from PET resins to PET-bottle forms), bottle cleaning (by air), syrup preparation, mixing, filling, labelling and packing. During all these processes, there is no water consumption.

All wastewater produced during the production steps of the beverage is treated at a municipal wastewater treatment plant. The concentrations of chemicals in the effluent of the wastewater treatment plant are equal and in some instances even lower than the natural concentrations in the receiving water body. With this assumption, the grey component of the operational water footprint is effectively zero.

Overhead operational water footprint

The overhead operational water footprint is the water consumed or polluted as a result of:

- Water consumption by employees (drinking water).
- Water consumption or pollution as a result of water use in toilets and kitchen.
- Water consumed or polluted due to washing of the working clothes of the employees.
- Water consumed or polluted due to cleaning activities in the factory.

- Water consumption in gardening.

The factory considered in this study produces a number of different beverage products; our beverage is just one of them. Therefore, only a fraction of the total overhead water footprint is attributed to our beverage product, based on the ratio of the annual value related to the production of this specific product to the annual value of all products produced in the factory. The annual production value of our beverage product is 10% of the total production value of all beverage products produced by the factory.

In this study we assume that drinking water is negligible and that there is no gardening. It is further assumed that all water used during the other activities specified above returns to the public sewerage system and is treated in a municipal wastewater treatment plant such that the effluent causes no grey water footprint. As a result, the overhead operational water footprint is estimated as zero.

3.3.2 Supply-chain water footprint

Supply-chain water footprint related to the product inputs

The supply-chain water footprint related to product inputs consists of the following components:

- Water footprint of product ingredients other than water (sugar, CO_2, phosphoric acid, caffeine from coffee beans, vanilla extract, lemon oil and orange oil).
- Water footprint of other inputs used in production (bottle, cap, labelling materials, packing materials).

Table 3.1 specifies, per ingredient, the precise amount contained in a 0.5 litre bottle. It also shows which raw material each ingredient underlies and what the country of origin of the raw material is. In the case of sugar, the study considers three alternative sources: sugar beet, sugar cane and maize (which are used to make high fructose maize syrup). Table 3.1 also specifies the amounts of the other inputs used, again per 0.5 litre bottle. The figures for the amounts used are based on realistic values, similar to the ones on the commercial market. During bottle production, 25% of the material consists of recycled material. This ratio is taken into account in the calculations by using a fraction of 0.75 to calculate the amount of new material used. A similar approach has been used for pallets, which have a lifespan of 10 years (fraction 0.1 applied to the total used).

Table 3.1. Ingredients and other items used for the sugar-containing carbonated beverage (per 0.5 litre bottle).

Item	Amount (grams)	Raw material	Origin of raw material
Sugar	50[1]	Sugar beet	Iran, Russia, USA, Italy, Spain, France, The Netherlands
Sugar	50[1]	Sugar cane	Cuba, Pakistan, Brazil, India, Peru, USA
Sugar	50[1]	HFSM	India, USA, France, China
CO_2	4	Ammonia by product	The Netherlands
Caffeine	0.05	Coffee beans	Colombia
Phosphoric acid	0.2	Phosphate rock – by chemical process	USA
Vanilla extract	0.01	Vanilla beans	Madagascar
Lemon oil	0.007	Lemon	World market
Orange oil	0.004	Orange	World market
Bottle - PET	19.5	Oil	World market
Closure - HDPE	3	Oil	World market
Label - PP	0.3	Oil	World market
Label glue	0.18	Glue	World market
Tray glue	0.015	Glue	World market
Tray cartoon - paperboard	2.8	Wood	World market
Tray shrink film - PE	1.6	Oil	World market
Pallet stretch wrap - PE	0.24	Oil	World market
Pallet label (2x) - coated paper	0.003	Wood	World market
Pallet - painted wood	0.09	Wood	World market

[1] Breedveld *et al.* (1998).

Table 3.2. Water footprint of the ingredients of the sugar-containing carbonated beverage.

Item	Raw material	Selected location	Water footprint of raw material (m^3/ton)			Process water requirement (m^3/ton)			Fractions for products used	
			Green	Blue	Grey	Green	Blue	Grey	Product fraction	Value fraction
Sugar	Sugar beet	Iran	21	298	36	0	0	0	0.16	0.89
Sugar	Sugar beet	Russia	89	123	16	0	0	0	0.16	0.89
Sugar	Sugar beet	USA	53	108	23	0	0	0	0.16	0.89
Sugar	Sugar beet	Italy	50	56	19	0	0	0	0.12	0.89
Sugar	Sugar beet	Spain	29	67	28	0	0	0	0.13	0.89
Sugar	Sugar beet	France	36	29	19	0	0	0	0.14	0.90
Sugar	Sugar beet	Netherlands	45	23	18	0	0	0	0.15	0.89
Sugar	Sugar cane	Cuba	310	214	20	0	0	0	0.14	0.86
Sugar	Sugar cane	Pakistan	29	402	26	0	0	0	0.14	0.86
Sugar	Sugar cane	Brazil	115	87	8	0	0	0	0.14	0.86
Sugar	Sugar cane	India	85	156	15	0	0	0	0.14	0.86
Sugar	Sugar cane	Peru	0	134	8	0	0	0	0.14	0.86
Sugar	Sugar cane	USA	95	79	10	0	0	0	0.14	0.86
Sugar	HFMS	India	1163	376	100	0	0	0	0.36	0.73
Sugar	HFMS	USA	156	136	64	0	0	0	0.36	0.73
Sugar	HFMS	France	100	99	90	0	0	0	0.36	0.73
Sugar	HFMS	China	328	177	118	0	0	0	0.36	0.73
CO_2	Ammonia by product	USA	0	0	0	0	83.5[1]	0	1	1
Phosphoric acid	Phosphate rock	USA	0	0	0	0	0	0	1	1
Caffeine	Coffee beans	Colombia	14470	0	0	0	0	0	0.0137	1
Vanilla extra	Vanilla	Madagascar	199383	0	0	0	0	0	0.025[2]	1
Lemon oil	Lemon	World average	559	0	0	0	0	0	0.4	1
Orange oil	Orange	World average	457	0	0	0	0	0	0.0021	1

[1] Van der Leeden *et al*. (1990).

[2] Dignum *et al.* (2001)

For the beverage ingredients, data on the water footprints of the raw materials, process water requirements, and product and value fractions, are presented in Table 3.2. The water footprints of the various forms of sugar from different countries have been taken mainly from Gerbens-Leenes and Hoekstra (2009). For four selected countries (France, Italy, Spain and the Netherlands), the water footprint of sugar beet is specifically calculated as part of the scope of this study. The water footprints of other ingredients are taken from Chapagain and Hoekstra (2004). For the other inputs used in the production of a 0.5 litre bottle of our beverage, water footprints of raw materials and process water requirements are presented in Table 3.3.

Table 3.3. Water footprint of raw materials and process water requirements for other inputs of a 0.5 litre bottle of sugar-containing carbonated beverage.

Item	Raw material	Selected location	Water footprint of raw material (m^3/ton)[1]			Process water requirement (m^3/ton)[1]		
			Green	Blue	Grey	Green	Blue	Grey
Bottle -PET	Oil	Sweden (raw) - Germany (process)	0	10	0	0	0	225
Closure - HDPE	Oil	Sweden (raw) - Germany (process)	0	10	0	0	0	225
Label - PP	Oil	Sweden (raw) - Germany (process)	0	10	0	0	0	225
Label glue	Glue	Germany	0	0	0	0	0	0
Tray glue	Glue	Netherlands	0	0	0	0	0	
Tray cartoon	Wood	Belgium	369.4[2]	0	0	0	0	180
Tray shrink film	Oil	Sweden (raw) - Germany (process)	0	10	0	0	0	225
Pallet stretch wrap	Oil	Sweden (raw) - Germany (process)	0	10	0	0	0	225
Pallet label	Wood	Finland (process)	369.4[2]		0	0	0	125
Pallet	Wood	Sweden (process) - Russia	369.4[2]		0	0	0	75

[1] Van der Leeden *et al*. (1990).

[2] Gerbens-Leenes *et al*. (2009a).

Overhead supply-chain water footprint

The overhead supply-chain water footprint originates from all goods and services used in the factory that are not directly used in or for the production process of one particular product produced in the factory. The factory produces other products than our 0.5 litre PET bottle of sugar-containing carbonated beverage as well, so the overhead water footprint needs to be allocated only partly to our product.

Goods that could be considered for the calculation of the overhead supply-chain water footprint are for example: construction materials and machineries used in the factory, office equipment and materials, cleaning equipment and materials, kitchen equipment and materials, working clothes used by employees, transportation, and energy for heating and power. This list can be extended further. For the scope of this study, it was decided to include some selected materials for the calculation of overhead water footprint in order to understand the influence of such elements on the total water footprint of the final product. The materials selected for assessment are the following:

- Construction materials (concrete and steel)
- Paper
- Energy in the factory (natural gas and electricity)
- Transportation (vehicles and fuel)

Table 3.4. List of selected goods and services for assessing the overhead supply-chain water footprint.

Item	Total amount used	Unit	Raw material	Amount of raw material	Unit of raw material	Lifespan of material	Yearly amount
Concrete	30000	ton	Cement	30000	ton	40	750
Steel	5000	ton	Steel	5000	ton	20	250
Paper	1	ton/year	Wood	1	ton/year	-	1
Natural gas	65000	GJ/year	Gas	65000	GJ/year	-	65000
Electricity	85000	GJ/year	Several	85000	GJ/year	-	85000
Vehicles	40	numbers	Steel	11.6	tons/vehicle	10	46.4
Fuel	150000	litres/year	Diesel	150000	litres/year	-	150000

The amounts of materials used in our factory are specified in Table 3.4. For paper and energy use in the factory and transportation fuels, annual amounts are given. For construction materials and vehicles, total amounts are given with a specification of the lifespan of the totals. The lifespan can be used to calculate annual figures from the totals. For the vehicles, it is assumed that average lifespan of a track is 10 years. Table 3.5 gives the water footprints of the raw materials relating to the overhead goods and the process water requirements.

The value of the 0.5 litre PET bottles of our beverage is 10% of the total value of products produced in the factory. Therefore, 10% of the total overhead water footprint of the factory will be allocated to our product. The annual production is 30 million bottles per year, so the overhead water footprint per bottle is found by dividing the overhead water footprint insofar allocated to our product by 30 million.

Table 3.5. Supply-chain water footprint of the selected overhead goods and services.

Item	Raw material	Selected location for the calculation of the water footprint	Water footprint of raw material (m^3/ton)			Process water requirement (m^3/ton)[1]		
			Green[2]	Blue[1]	Grey	Green	Blue	Grey
Concrete	Cement	Belgium (process)	0	0	0	0	0	1.9
Steel	Steel	Sweden (process) - USA (raw material)	0	4.2	0	0	0	61
Paper	Wood	Finland (process)	369.4	0	0	0	0	125
Natural gas	Gas	World average	0	0	0	0	0	0.11
Electricity	Several	World average	0	0	0	0	0	0.47
Vehicles	Steel	Sweden (process) - USA (raw material)	0	4.2	0	0	0	61
Fuel	Diesel	World average	0	0	0	0	0	1.06

[1] Van der Leeden *et al.* (1990).

[2] Gerbens-Leenes *et a*l. (2009a).

3.4 Results

3.4.1 Water footprint of a 0.5 litre PET-bottle sugar-containing carbonated beverage

The total water footprint of our beverage amounts to 169 to 309 litres (Table 3.6). In calculating the total water footprint of the product, the amounts of all ingredients and other inputs are kept constant; only the type and origin of the sugar is changed in order to understand the effect of sugar type and production location on the total water footprint of the beverage. The effect of the type and origin of sugar used is shown in Figure 3.3.

Table 3.6. The total water footprint of a 0.5 litre PET-bottle sugar-containing carbonated beverage.

	Water footprint (litres)			
Item	**Green**	**Blue**	**Grey**	**Total**
Operational water footprint	0	0.5	0	0.5
Supply-chain water footprint*	134.5-252.4	7.4-124	9.2-19.7	168-308.9
Total*	**134.5-252.4**	**7.9-124.5**	**9.2-19.7**	**168.5-309.4**

*The range reflects the fact that we have considered different types and origin of the sugar input.

The total water footprint of the beverage is the highest (309 litres) when the sugar originates from cane sugar from Cuba, and the lowest (169 litres) when the sugar comes from beet sugar from the Netherlands. If we compare the beet sugars, our product has the highest water footprint when beet sugar is from Iran (241 litres) followed by Russia (206 litres), USA (194 litres), Italy (189 litres), Spain (185 litres), France (170 litres) and the Netherlands (169 litres). For sugar cane, our beverage has the highest water footprint when we take the cane from Cuba (309 litres), followed by Pakistan (283 litres), India (221 litres), Brazil (207 litres), USA (199 litres) and Peru (186 litres). When we use HFMS as a sweetener, the order is: India (309 litres), China (206 litres), USA (179 litres) and France (172 litres).

Almost the entire water footprint of the product is stemming from the supply-chain water footprint (99.7-99.8%). This shows the importance of a detailed supply chain assessment. Common practice in business water accounting, however, is to focus on operational water consumption. The results of this study imply that compared to the traditional water use indicator (water withdrawal for the own operations), the water footprint provides much more information. In this particular case, the operational water footprint cannot be lowered because it is precisely equal to the amount needed as an ingredient to the beverage. The traditional indicator of water withdrawal would show a larger number, because withdrawals include return flows, while the water footprint excludes those, because return flows can be reused, so they do not impact on the available water resources like consumptive water use does. In our case, there is no consumptive water use and wastewater is treated properly before returned to the system.

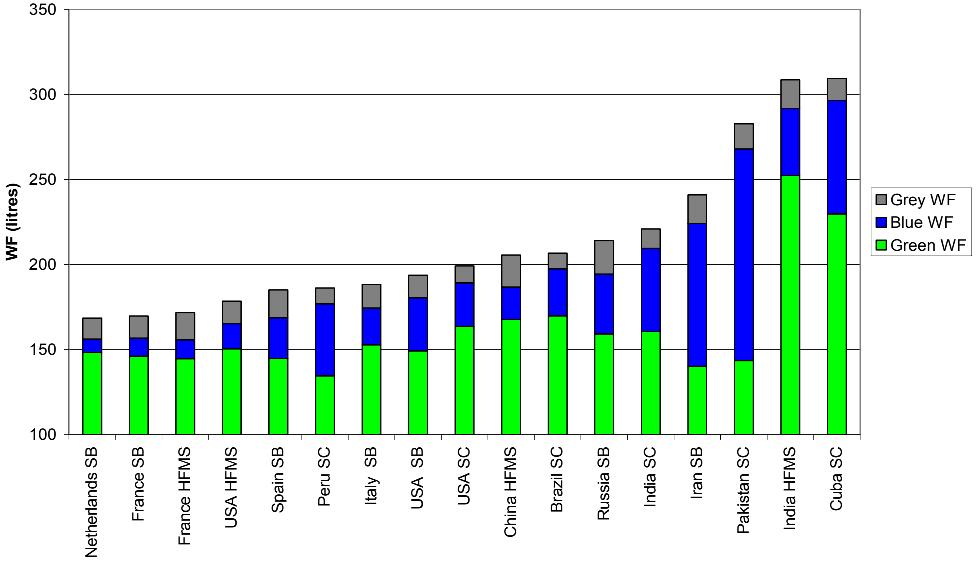

Figure 3.3 The total water footprint of 0.5 litre PET-bottle sugar-containing carbonated beverage according to the type and origin of the sugar (SB=Sugar Beet, SC=Sugar Cane, HFMS= High Fructose Maize Syrup).

Figure 3.4 shows the colour composition of the total water footprint of the product for two different countries. Pakistan has the one with the highest ratio for blue water footprint. The Netherlands has the highest ratio for green water footprint.

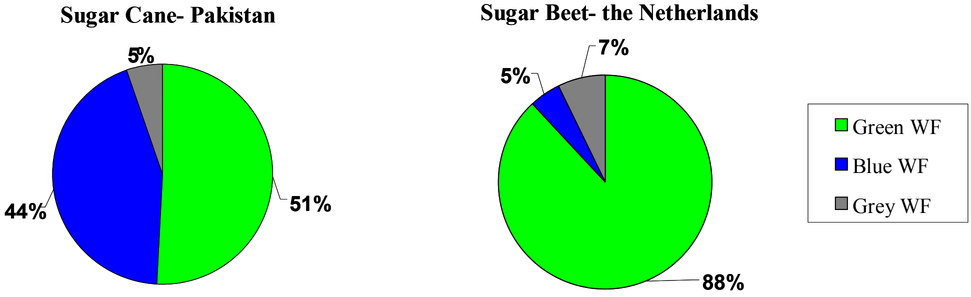

Figure 3.4 The water footprint colour composition of a 0.5 litre PET-bottle sugar-containing carbonated beverage for Pakistan (sugar cane) and the Netherlands (sugar beet).

Supply-chain water footprint

The supply-chain water footprint of our beverage is calculated as a summation of the water footprints of all inputs (both ingredients and other inputs) and the water footprint of overhead activities. Table 3.7 presents the various components of the supply-chain water footprint of our beverage product.

Sugar is one of the main water consuming ingredients in our beverage. One of the aims of this paper is to understand the effect of sugar type and origin on the total water footprint of the beverage. For this purpose, three different commonly used sugar types are selected: sugar beet, sugar cane and HFMS. For each type, some production countries are selected for the calculation, which have high, low and average water footprints. Table 3.8 presents the water footprint of the sugar input in our beverage product as a function of sugar type and origin.

Table 3.7. The supply-chain water footprint of a 0.5 litre PET-bottle sugar-containing carbonated beverage.

Item	**Supply-chain water footprint (litres)**			
	Green	**Blue**	**Grey**	**Total**
Sugar	see Table 3.8			
CO_2	0	0.3	0	0.33
Phosphoric acid or citric acid (e338)	0	0	0	0
Caffeine	52.8	0	0	52.8
Vanilla extract	79.8	0	0	79.8
Lemon oil	0.01	0	0	0.01
Orange oil	0.9	0	0	0.9
Bottle – PET	0	0.2	4.4	4.5825
Closure – HDPE	0	0.03	0.68	0.7
Label – PP	0	0.003	0.068	0.07
Label glue (not included)	0	0	0	0
Tray glue (not included)	0	0	0	0
Tray cartoon - paperboard	1	0	0.5	1.5
Tray shrink film - PE	0	0.02	0.36	0.38
Pallet stretch wrap - PE	0	0.003	0.054	0.057
Pallet label (2x) - coated paper	0.001	0	0.0004	0.0015
Pallet - painted wood	0.033	0	0.007	0.04
Concrete	0	0	0.005	0.005
Steel	0	0.004	0.05	0.054
Paper	0.0012	0	0.0004	0.0016
Natural Gas	0	0	0.024	0.024
Electricity	0	0	0.13	0.13
Vehicles	0	0.001	0.009	0.01
Fuel	0	0	0.5	0.5
Total	**134.5-252.4**	**7.4-124**	**9.2-19.7**	**168-308.9**

When we choose to use sugar beet as sugar source of our hypothetical beverage, the water footprint of the sugar input can vary from 26 litres per 0.5 litre bottle (when the sugar beets are grown in the Netherlands) to 98.5 litres (Iran). If our source is sugar cane, the water footprint of the sugar input can vary from 43.9 litres per bottle (Peru) to 167 litres (Cuba). If we would use HFMS as a sweetener, not so usual in the world but common in the

US, the water footprint of the sugar input will range from 29.3 litres per bottle (when the maize comes from France) to 166 litres (India). It is important to identify and analyse the colours of the water footprint of the product in order to assess the impacts of the water footprints. The highest *blue* water footprint related to the sugar input alone is 124 litres with sugar cane from Pakistan and the lowest is 7 litres with sugar beet from the Netherlands. The *grey* water footprint of the sugar input is the lowest when the sugar intake is cane sugar from Brazil (2.4 litres), and highest with HFMS from China (12 litres). This analysis shows that sugar type and production location affect the total water footprint of the product and the ratios green/blue/grey significantly. It shows that including the spatial dimension in water footprint assessment is indeed important.

Table 3.8. The water footprint of the sugar input for a 0.5 litre PET-bottle sugar-containing carbonated beverage.

Item	Water footprint (litres)				Remarks[1]
	Green	Blue	Grey	Total	
Beet sugar					
Iran[1]	5.7	82.8	10.0	98.5	Highest WF, highest blue WF
Russia[1]	24.6	34.1	4.5	63.3	High WF, big producer
USA[1]	14.7	30.1	6.4	51.2	Second biggest producer in the world
Italy[2]	18.6	20.8	7.1	46.5	Close to global average WF
Spain[2]	10.0	23.1	9.7	42.8	Close to global average WF
France[2]	11.7	9.5	6.2	27.4	Biggest producer in the world
Netherlands[2]	13.6	7.0	5.4	26.0	Very low WF
Cane sugar[1]					
Cuba	95.2	65.7	6.2	167.0	Highest WF
Pakistan	9.0	123.5	8.0	140.4	High WF, highest blue WF
Brazil	35.3	26.6	2.4	64.3	Biggest producer in the world
India	26.2	47.9	4.6	78.6	Second biggest producer in the world
Peru	0.0	41.3	2.6	43.9	Lowest WF
USA	29.3	24.4	3.2	56.8	Close to world average
HFMS 55[1]					
India	117.9	38.2	10.2	166.2	Highest WF
USA	15.9	13.8	6.5	36.1	Biggest producer in the world and highest rate of maize usage for sugar input
France	10.1	10.0	9.2	29.3	Low WF
China	33.3	17.9	12.0	63.2	Close to global average WF

[1] Gerbens-Leenes and Hoekstra (2009).

[2] Own calculations.

In our hypothetical beverage, the amounts of vanilla extract (0.01 g) and caffeine from coffee beans (0.05 g) inputs are very small in the total amount of the beverage. Although their physical content in the beverage is small (0.09% for caffeine and 0.02% for vanilla), their contribution to the total water footprint of the product is very high (maximum 33% for caffeine and 50% for vanilla). This study reveals that, without prior knowledge about the relevance of different inputs, a detailed and comprehensive supply-chain analysis is essential for the calculation of the water footprint of a product. Even small ingredients can significantly affect the total water footprint of a product.

Operational water footprint

The operational water footprint of a 0.5 litre PET-bottle sugar-containing carbonated beverage has a number of components as shown in Table 3.9. Both green and grey water footprints are zero. The blue water footprint is 0.5 litre of water for one bottle. The total operational water footprint is thus no more than the water used as ingredient of the beverage. The 'water footprint' of the operations is lower than the 'water withdrawal' of the factory, because all water withdrawn by our hypothetical factory is returned (except for the water used as ingredient for the beverage) and purified before disposal.

Table 3.9. The operational water footprint of a 0.5 litre PET-bottle sugar-containing carbonated beverage.

	Operational water footprint (litres)			
Item	**Green**	**Blue**	**Grey**	**Total**
Inputs				
Direct water used for a 0.5 litre PET (as ingredient)	0	0.5	0	0.5
Net water used in production steps	0	0	0	0
Bottle making	0	0	0	0
Bottle cleaning (by air)	0	0	0	0
Ingredients mixing	0	0	0	0
Packing	0	0	0	0
Overhead				
Domestic Water Consumption	0	0	0	0
Total operational water footprint	**0**	**0.5**	**0**	**0.5**

3.5 *Impact assessment of a 0.5 litre PET-bottle sugar-containing carbonated beverage*

According to its definition, the water footprint concept is a geographically explicit indicator, not only showing volumes of water use and pollution, but also showing the various locations where the water is used (Hoekstra and Chapagain, 2008). This means, water footprint analysis of a business/product shows the impact of business activities on nature and society by answering two fundamental questions: where (location) and when (time). It is also useful to show the blue, green and grey components of the water footprint of a business/product, because the impact of the water footprint will depend on whether it concerns the evaporation of abstracted ground or surface water, the evaporation of rainwater used for production or pollution of freshwater.

Assessment of the impacts of a water footprint starts with quantifying, localizing and describing the colour of the water footprint. Next step is to identify the vulnerability of the local water systems where the footprint is located, the actual competition over the water in these local systems and the negative externalities associated with the use of the water. This kind of an assessment may lead to a corporate water strategy to reduce and offset the impacts of the water footprint (Hoekstra, 2008). The goals of a business with respect to reducing and offsetting the impacts of its water footprint can be prompted by the goal to reduce the business risks related to its freshwater appropriation. Alternatively, they can result from governmental regulations with respect to water use and pollution.

It is important to understand and evaluate the environmental impacts of all crops if we are to achieve sustainable production systems. Understanding the impact of sugar beet, sugar cane and HFMS are particularly important as there are different countries where they can be grown, and also because there is a growing interest in their potential as a source for biofuel (Gerbens-Leenes and Hoekstra, 2009).

For the impact assessment of sugar usage, we compare the water footprint of sugar beet, cane and HFMS as quantified in the previous section with the water scarcity in the different regions where the water footprint is located following the method developed by Van Oel *et al.* (2008). For this purpose, a water scarcity indicator by Smakhtin *et al.*

(2004a; 2004b) was used. This indicator deals with the withdrawal-to availability ratio per river basin taking into account the environmental water requirements, which are subtracted from runoff.

Sugar beet

With a population of more than 65 million people, Iran is actually one of the most water-scarce countries of the world. It is estimated that the average annual supply of renewable freshwater per person will fall from 1,750 (2005) to 1,300 m^3 (2020). According to the 'Falkenmark thresholds', a country will experience periodic water stress when freshwater availability is below 1,700 m^3 per person per year (Falkenmark and Rockström, 2004). More than 94 percent of the total annual water consumption in Iran is used for agriculture, so agriculture plays a significant role in water stress in the country. In addition, the productivity of water (yield per unit of water) is very low. The water footprint of Iranian sugar beet is one of the highest in the world (Gerbens-Leenes and Hoekstra, 2009). The Iranian sugar beet usage in our product leads to 99 litres of water consumption per bottle, 84% of which are from blue water sources. Amongst all countries, sugar beet cultivation in Iran requires the most irrigation (highest blue water footprint). This leads to serious water problems in sugar beet cultivation regions, especially where the production rate is high. One-third of the country's sugar factories are in the three provinces of Razavi Khorasan, Northern Khorasan and Southern Khorasan Iran that experience mostly arid climatic conditions and currently experiencing extreme water shortages. This problem has become more visible, especially in these specific parts of the country, due to recent droughts (Larijani, 2005).

Another country with a high water footprint of sugar intake is Russia with a sugar-related water footprint of 63 litres per bottle. Similar to Iran, the blue water footprint of sugar beet in Russia is high, i.e. 53% of the total water footprint. The most important problem due to sugar beet cultivation in Russia is in the area north of the Black Sea. Pollution in the rivers Dnieper and Don, which flow to the Black Sea, is causing serious environmental damage to the Black Sea ecosystem. In 1992, The Russian Federation's Committee on Fishing reported several cases of water bodies were completely contaminated by agricultural runoff. Besides pollution by excessive use of fertilizers, irrigation has also resulted in water scarcity in some areas (Gerbens-Leenes and Hoekstra, 2009).

Andalucia is a clear hotspot since it is a water scarce region with a high water footprint in relation to sugar beet production. Sugar beet irrigation in this region has contributed to lower water levels in the Guadalquivir River, limiting water reaching important wetlands during summer (WWF, 2004).

The water quality issue is a major concern since the overuse of fertilizers on beet crops is typical of farming in general (WWF, 2004). Environmental impacts generally arise because the nutrients in the fertilizers are not entirely taken up by the crop but move into the environment. The runoff of nitrate and phosphate into lakes and streams can contribute to accelerated eutrophication and the proliferation of toxic microalgae. In the Seine-Normandy basin, irrigation has little quantitative impact on the resource, but does, however, have an indirect impact on quality because it favours intensive farming techniques and spring crops, which leave the soil bare for long periods of the year and increase the chemical load in the rivers by leaching and draining (UNESCO, 2003). This has a harmful effect on both the environment and other water uses. Improving water quality is still a major concern of the basin, where non-point source pollution from farming and urban areas is still a major problem as nitrate, pesticide and heavy metal concentrations continue to increase (ibid.).

Sugar cane

Sugarcane is the most important plant in Cuba and it was the most important foreign exchange earner of the tropical island for decades. The water footprint of sugar intake for our beverage is the highest when sugar is sugar cane sourced from Cuba, with 167 litres per bottle. Sugar cane production in Cuba has also the highest water footprint in the world compared to other sugar types and production locations. Cuba has been facing several environmental problems for the last decades in relation to sugar cane production. Cuba has high-quality resources of karst water, but the quality of this water is highly susceptible to pollution. Pollution resulting from sugar cane factories is one of the main reasons that the quality of karst aquifers has deteriorated (León and Parise, 2008). In addition, the untreated wastewater discharge from sugar factories in Cuba has led to oxygen deficiency in rivers and the dominance of aquatic macrophytes, which results in thick mats of weeds. This situation partially blocks the water delivery capacity of canals, which has negative effects on fishing and tourism (WWF, 2004). Due to sugar cane cultivation, deforestation in Cuba has become a major environmental problem (Monzote, 2008). Cuba's forest area has also been drastically decreased as a result of demand for lumber; the sugar cane industry alone annually consumes 1 million cubic meters of firewood (Cepero, 2000).

Another country with a high water footprint of sugar cane is Pakistan. If we choose Pakistani sugar cane for our product, the water footprint of sugar intake will be 140 litres per bottle. The sugar cane in Pakistan heavily depends on irrigation; the blue water footprint constitutes 88% of the total water footprint. Water abstractions for irrigation cause water shortage in the production regions and serious environmental problems. The Indus River is the major water resource of Pakistan. The freshwater reaching the Indus Delta has significantly decreased (90%) as a result of over-usage of water sources in the Indus basin. Sugar cane is one of the main water consuming agricultural products in the basin. The decrease in freshwater flow to the Indus Delta has negative impacts on the biodiversity of the Delta (decrease of mangrove forestlands, and danger of extinction of the blind river dolphin). Additionally, excessive water use in sugar cane cultivation areas also leads to salinity problems in Pakistan (WWF, 2004). Moreover, untreated wastewater discharge from sugar mills causes depletion of available oxygen in water sources which results in endangering fish and other aquatic life (Akbar and Khwaja, 2006).

Being the largest sugar cane producer in the world, Brazil has faced several negative impacts of sugar cane production. However, most of the sugar cane produced is used as raw material for ethanol production. Extensive sugar cane production and demand in Brazil has led to deforestation of rain forests. Moreover, sugarcane fields in the state of San Paulo are reported to cause air pollution due to pre-harvest burning (WWF, 2004). Water pollution due to sugar cane industry and sugar cane agricultural practice (fertilizers and pesticides) is another major environmental problem in Brazil (Gunkel *et al*., 2006).

Like other countries, India is also facing environmental problems due to sugar cane cultivation. In the Indian state of Maharashtra, sugar cane irrigation uses 60% of the total irrigation supply, which causes substantial groundwater withdrawals (WWF, 2004). India’s largest river, the Ganges, experiences severe water stress. Sugar cane is one of the major crops cultivated in the area and increases water scarcity (Gerbens-Leenes and Hoekstra, 2009). Another problem resulting from sugar cane cultivation and sugar processing activity in India is the pollution of surface and groundwater resources (Solomon, 2005).

Other ingredients and inputs

The results presented earlier in this chapter show that vanilla, which is part of the natural flavour of our beverage, contributes largely to the overall water footprint (from 27% to 50%). The source of the vanilla is Madagascar, which is the main vanilla producing country in the world. Cultivation of vanilla is one of the most labour-intensive agricultural crops and it takes up to three years before the crop can be harvested. Harvested flowers need a process called curing in order to take its aroma. This process needs heating of the vanilla beans in hot water (65 degrees Celsius) for three minutes, which causes most environmental problems in the production countries. Thermal pollution occurs as a result of hot water discharged into freshwater systems, causing sudden increases in the temperature of the ambient water systems above ecologically acceptable limits. In addition to water contamination by means of temperature changes, the necessity of obtaining wood, the main energy source of heating, causes deforestation of rainforests (TED, 2003).

Another small ingredient of our hypothetical beverage is caffeine. Although the amount of caffeine used in the product is small, the water footprint is very high (53 litres per bottle). The caffeine is sourced from coffee beans produced in Colombia, which is one of the biggest coffee producers in the world. Two major problems exist in Colombia due to coffee cultivation: loss of bird species and soil erosion. Additionally, pollution of surface and ground water resources resulting from usage of fertilizers is a major environmental problem due to coffee cultivation (TED, 2001).

The oil based materials used for the bottle of our beverage (PET-bottle, cap, stretch films and labels) have particularly a grey water footprint. In PE production, large amounts of water are used for cooling. Cooling water is considered as grey water as it increases the temperature of the receiving freshwater bodies more than what is acceptable from an ecological point of view. Water quality criteria for aquatic ecosystems indicate that water temperature may not increase by more than a few degrees Celsius compared to natural conditions (CEC, 1988). Additional freshwater sources are required to dilute hot water stemming from cooling water (to decrease the temperature of discharged cooling water in order to meet standards with respect to maximum increase of water temperature).

3.6 Conclusion

The total water footprint of our beverage is calculated as minimum 169 litres (using sugar beet from the Netherlands) and maximum 309 litres (using sugar cane form Cuba). The operational water footprint of the product is 0.5 litres, which forms 0.2-0.3% of the total water footprint. The supply-chain water footprint constitutes 99.7-99.8% of the total water footprint of the product.

The operational water footprint of the 0.5 litre PET-bottle sugar-containing carbonated beverage consists of two components: the operational water footprint the 'overhead water footprint'. The first is equal to the water incorporated into the product, which is 0.5 litres. There is no other operational water footprint than this, because there is no other water consumption or pollution in the factory related to the production of the product. There is water use in the factory for general purposes such as flushing toilets, cleaning working clothes, and washing and cooking in the kitchen, but all water used is collected and treated in a public wastewater treatment plant before it is returned into the environment. Thus, the net abstraction from the local water system for those activities is zero.

The supply-chain water footprint of the product also consists of two components: related to product inputs (ingredients and other inputs) and overhead. Most of the supply-chain water footprint of the product is coming from its ingredients (95-97%). A smaller fraction of the supply-chain water footprint comes from the other inputs (2-4%), mainly from the PET-bottle. The overhead water footprint constitutes a minor fraction of the supply-chain water footprint (0.2-0.3%).

The main impacts of the hypothetical product are stemming from the grey and blue water footprints of the product. Ingredients like sugar, vanilla, caffeine (coffee) cause contamination of natural freshwater sources (grey water footprint) because of the use of fertilizers and pesticides. The biggest impact of the water footprint of the beverage is related to the sugar ingredient. Many sugar producing countries are water-rich countries where the water footprint does not relate to water stress. There are, though, several localized hotspots, such as the sugar beet production in the Andalucía region in the South of Spain, sugar cane production in Pakistan (Indus River) and India (Ganges River), and sugar beet from Iran. With regard to water quality, pollution by nitrates is an issue in several regions, such as the case of Northern France, Russia (Black Sea), India, Pakistan, Cuba, Brazil, Iran and China. A rational N fertilization is important to reduce the environmental impact of fertilization and to increase profitability in crop production. Better management practices to reduce the environmental impacts in the sugar industry do not necessarily imply reduced productivity and profits; indeed, measures to address environmental impacts can provide economic benefits for farmers or mills through cost savings from more efficient resource use. In addition, mostly sugar cane production relates to deforestation like in Cuba and Brazil. Other negative effects of sugar production are impacts on biodiversity (decrease of mangrove forestlands, and danger of extinction of the blind river dolphin in the Indus Delta).

The results of this study show the importance of a detailed supply-chain assessment in water footprint accounting. Common practice in business water accounting is mostly restricted to the analysis of operational water use. This study shows that compared to the supply-chain water footprint, the operational side is almost negligible. The results of this study imply that compared to other water accounting tools, the concept of the water footprint provides a more comprehensive tool for water accounting.

The study shows that the water footprint of a beverage product is very sensitive to the production locations of the agricultural inputs. Even though the amount of sugar is kept constant, the water footprint of our product significantly changes according to the type of sugar input and production location of the sugar. Additionally, the type of water footprint (green, blue and grey) changes according to location, which are mainly driven by the difference in climatic conditions and agricultural practice in the production locations. These results reveal the importance of the spatial dimension of water footprint accounting.

The study reveals that detailed and comprehensive supply-chain analysis is essential for the calculation of the water footprint of a product. It shows that even small ingredients can significantly affect the total water footprint of a product. On the other hand, the study also shows that many of the components studied hardly contribute to the overall water footprint.

The general findings of this study with respect to the ratio of operational to supply-chain water footprint and the relative importance of ingredients, other inputs and overhead can be extended to other beverages similar to our hypothetical beverage. The major part of the water footprint of most beverages will be stemming from the supply chain. The operational water footprint of the beverages similar to ours will be negligible compared to the water footprint of the ingredients. This shows the importance of focusing cooperate water policy towards to supply chain rather than operational water use.

This is the first study quantifying the overhead water footprint of a product. Strictly spoken, this component is part of the overall water footprint of a product, but it was unclear how relevant it was. This study reveals that the overhead component is not important for this kind of studies and is negligible in practice.

By definition, the water footprint is a geographically explicit indicator, not only showing volumes of water use and pollution, but also showing the various locations where the water is used and the periods of the year in which the water is used (Hoekstra and Chapagain, 2008). The question in practical applications is, however, whether it is feasible to trace the precise locations and timing of water use in the supply chain of a product. In the current water footprint study for a 0.5 litre PET-bottle sugar-containing carbonated beverage we show that it is feasible to trace water use in the supply-chain relatively well, based on a desk study only. Even better and more precise results could be obtained in a more elaborate study including visits to the suppliers and finally to the farmers and mining industries producing the primary ingredients. Knowing the blue, green and grey components of the water footprint of a product and the precise locations and timing of water use is essential for water footprint impact assessment, which in turn is key for formulating mitigating policies. Accurate material flow accounting along the full supply-chain of a product would simplify water footprint accounting.

4 Sustainability of national consumption from a water resources perspective: A case study for France[3]

Abstract

In recent years, it has become increasingly evident that local water depletion and pollution are often closely tied to the structure of the global economy. It has been estimated that twenty per cent of the water consumption and pollution in the world relates to the production of export goods. For developing a wise national water policy, it is relevant to consider the linkages between consumed goods in a country and impacts on freshwater systems where the goods are produced. The objective of this study is to identify and analyse how French water resources are allocated over various purposes, and to examine where the water footprint of French production violates local environmental flow requirements and ambient water quality standards. Additionally, the aim is to understand the water dependency of French consumption and the sustainability of imports. The total water footprint of production and consumption in France is 90 billion m^3/year and 106 billion m^3/year respectively. The blue water footprint of production is dominated by maize production. The basins of the Loire, Seine, Garonne, and Escaut have been identified as priority basins where maize and industrial production are the dominant factors for the blue water scarcity. About 47% of the water footprint of French consumption is external and related to imported agricultural products. Cotton, sugar cane and rice are the three major crops with the largest share in France's external blue water footprint of consumption and identified as critical products in a number of severely water-scarce river basins. The basins of the Aral Sea and the Indus, Ganges, Guadalquivir, Guadiana, Tigris & Euphrates, Ebro, Mississippi and Murray rivers are some of the basins that have been identified as priority basins regarding the external blue water footprint of French consumption. The study shows that analysis of the external water footprint of a nation is necessary to get a complete picture of the relation between national consumption and the use of water resources. It provides understanding of how national consumption impacts on water resources elsewhere in the world.

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[3] Based on Ercin et al. (2012b)

4.1 Introduction

Water plays a key role in life on our planet. It is essential not only for direct uses such as for the provision of drinking water, growing food and the production of energy and other products, but also for ensuring the integrity of ecosystems and the goods and services they provide to humans. Freshwater is a renewable resource; however, its annual availability is limited. Annual freshwater use in many places exceeds the limit of the water available, which has resulted in river flows that are below environmental flow requirements, declining groundwater levels and pollution of water bodies.

In recent years, it has become increasingly evident that local water depletion and pollution are often closely tied to the structure of the global economy (Hoekstra and Chapagain, 2007). It has been estimated that about twenty per cent of the water consumption and pollution in the world relates to the production of export goods (Hoekstra and Mekonnen, 2012a). International trade in commodities implies long-distance transfers of water in virtual form, where virtual water is understood as the volume of water that has been used to produce a commodity and that is thus virtually embedded in it (Chapagain and Hoekstra, 2008). Knowledge about the virtual-water flows entering and leaving a country can cast a new light on the actual water scarcity of a country. For developing a wise national water policy, it is also relevant to consider the linkages between consumed goods in a country and impacts on freshwater systems where the goods are produced.

The water footprint is an indicator of freshwater use that looks not only at direct water use of a consumer or producer, but also at the indirect water use. The water footprint can be regarded as a comprehensive indicator of freshwater resources appropriation, next to the traditional and restricted measure of water withdrawal. It is a multi-dimensional indicator, showing water consumption volumes by source and polluted volumes by type of pollution; all components of a total water footprint are specified geographically and temporally (Hoekstra et al., 2011).

The objective of this study is to carry out a water footprint assessment for France from both a production and consumption perspective. The aim of the assessment from the production perspective is to identify and analyse how French water resources are allocated over various purposes, and examine where the water footprint of production within France violates local environmental flow requirements and ambient water quality standards. Additionally, the aim is to quantify which volumes of French water resources are allocated for making products for export and to assess the impact related to this water footprint for export. The assessment from the consumption perspective focuses on the analysis of the external water footprint of French consumption, to get a complete picture of how national consumption translates to water use, not only in France, but also abroad, and to assess French dependency on external water resources and the sustainability of imports.

The study starts with a quantification and mapping of the water footprint of the agricultural and industrial sectors and of domestic water supply within France. Next, virtual water imports into France and virtual water exports leaving France are quantified, by traded commodity. Subsequently, the internal and external water footprint of French consumption is analysed. Finally, it has been analysed which components of the French blue water footprints of production and consumption contribute to blue water scarcity in specific river basins and which products are responsible herein.

There are several similar water footprint studies in the literature with a focus on a specific country. Studies have been carried out, for example, for Belgium (Vincent et al., 2011), China (Hubacek et al., 2009; Ma et al., 2006; Zhao et al., 2009), Germany (Sonnenberg et al., 2009), India (Kampman et al., 2008), Indonesia (Bulsink et al., 2010), the Netherlands (Van Oel et al., 2009), Spain (Garrido et al., 2010); and the UK (Chapagain and Orr, 2008). These studies mainly focussed on the quantification of the water footprints, were not based on a high-resolution spatial analysis and excluded an assessment of the sustainability of the water footprint. Impacts of water footprints on a national scale are partially addressed in Van Oel et al. (2009) for the Netherlands, Kampman et al. (2008) for India and Chapagain and Orr (2009) for Spanish tomatoes. However, these studies lack spatial detail as will employed in the current study, which will incorporate data on monthly blue water scarcity at the level of river basins to assess how blue water footprints of production and consumption contribute to water scarcity at river basin level.

From a methodological point of view, this study improves upon the previous country-specific water footprint studies in three ways, following the global study by Mekonnen and Hoekstra (2011b). First, the water footprints of production and consumption are mapped at a high level of spatial detail. Second, the analysis explicitly includes green, blue and grey water footprints. Finally, we make a substantial step beyond quantifying and mapping the country's water footprint of production and consumption by analysing how different components in the water footprint may contribute to blue water scarcity in different river basins and identifying which products are behind those contributions.

4.2 Method and data

4.2.1 Water footprint accounting

This study follows the methodology and terminology of water footprint assessment as described in the Water Footprint Assessment Manual (Hoekstra *et al.*, 2011). The water footprint is an indicator of water use that looks at both direct and indirect water use of a consumer or producer. The water footprint of an individual or community is defined as the total volume of freshwater that is used to produce the goods and services consumed by the individual or community. Water use is measured in terms of water volumes consumed (evaporated or incorporated into the product) and polluted per unit of time. A water footprint has three components: green, blue and grey. The blue water footprint refers to consumption of blue water resources (surface and ground water). The green water footprint is the volume of green water (rainwater) consumed, which is particularly relevant in crop production. The grey water footprint is an indicator of the degree of freshwater pollution and is defined as the volume of freshwater that is required to assimilate the load of pollutants based on existing ambient water quality standards. The water footprint of production and consumption in France is quantified according to the national water footprint accounting scheme as shown in Figure 4.1.

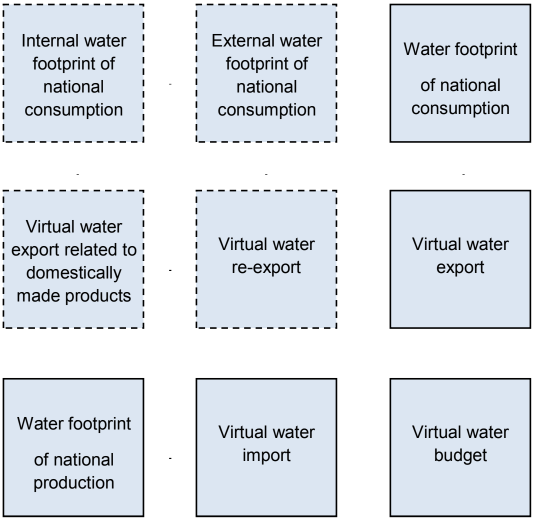

Figure 4.1. The national water footprint accounting scheme (Hoekstra et al., 2011).

The 'water footprint of national production' refers to the total freshwater volume consumed or polluted within the territory of the nation. This includes water use for making products consumed domestically but also water use for making export products. It is different from the 'water footprint of national consumption', which refers to the total amount of water that is used to produce the goods and services consumed by the inhabitants of the nation. This refers to both water use within the nation and water use outside the territory of the nation, but is restricted to the water use behind the products consumed within the nation. The water footprint of national consumption thus includes an internal and external component. The internal water footprint of national consumption is defined as the use of domestic water resources to produce goods and services consumed by the national population. It is the sum of the water footprint within the nation minus the volume of virtual-water export to other nations insofar as related to the export of products produced with domestic water resources. The external water footprint of national consumption is defined as the volume of water resources used in other nations to produce goods and services consumed by the population in the nation considered. It is equal to the virtual-water import into the nation minus the volume of virtual-water export to other nations because of re-export of imported products.

The water footprint of crops and derived crop products produced in France or elsewhere were obtained from Mekonnen and Hoekstra (2010a, 2011a), who estimated the global water footprint of crop production with a crop water use model at a 5 by 5 arc minute spatial resolution. The water footprint of animal products that are produced in France were taken from Mekonnen and Hoekstra (2010b, 2012). The data related to the water footprint of production and consumption in France and the virtual water flows to and from France were taken from Mekonnen and Hoekstra (2011b). In all cases, data refer to the period 1996-2005.

4.2.2 Identifying priority basins and products

For the blue water footprint of French production and consumption, some additional analysis was carried out in order to identify river basins of concern. After we quantified and mapped the blue water footprints of French production and consumption, we estimated which parts of both water footprints are situated in river basins with moderate to severe water scarcity during part of the year. Monthly blue water scarcity values for the major river basins around the world were taken from a recent global water scarcity study (Hoekstra and Mekonnen, 2011; Hoekstra et al., 2012). The blue water scarcity values in that study were calculated by taking the aggregated blue water footprint per basin and per month over the blue water availability in that basin and month. The latter was taken as natural runoff in the basin minus a presumptive standard for the environmental flow requirement in the basin. They classified blue water scarcity values into four levels:

- low blue water scarcity (<100%): the blue water footprint is lower than 20% of natural runoff and does not exceed blue water availability; river runoff is unmodified or slightly modified; environmental flow requirements are not violated.
- moderate blue water scarcity (100-150%): the blue water footprint is between 20 and 30% of natural runoff; runoff is moderately modified; environmental flow requirements are not met.
- significant blue water scarcity (150-200%): the blue water footprint is between 30 and 40% of natural runoff; runoff is significantly modified; environmental flow requirements are not met.

- severe water scarcity (>200%): the monthly blue water footprint exceeds 40% of natural runoff, so runoff is seriously modified; environmental flow requirements are not met.

The following three criteria have been used to identify priority basins regarding the various components of the blue water footprint of French production or consumption: level of water scarcity over the year in the basin where the water footprint component is located, the size of the blue water footprint of French production or consumption located in the basin (agricultural and industrial products separately), and the significance of the contribution of a specific product to the total blue water footprint in the basin in the scarce month.

A specific river basin is identified as a ‘priority basin’ related to France's water footprint of production or consumption of agricultural products if three conditions are fulfilled: (a) the river basin experiences *moderate, significant or severe* water scarcity in any specified period of the year; (b) the French blue water footprint of production or consumption of agricultural products located in that basin is *at least 1%* of total blue water footprint of production or consumption of agricultural products; and (c) the contribution of any specific agricultural commodity to the total blue water footprint in that specific basin in the period of scarcity is significant (*more than 5%*). In addition, a river basin is also identified as a priority basin if the following two conditions are met: (a) the water scarcity in the river basin is *severe* during part of the year; and (b) the contribution of any specific agricultural commodity produced or consumed in France to the total blue water footprint in that specific basin in the period of scarcity is very significant (*more than 20%*).

A river basin is identified as a priority basin related to France's water footprint of production or consumption of industrial products if three conditions are fulfilled: (a) the river basin experiences *moderate, significant or severe* water scarcity in any specified period of the year; (b) the French blue water footprint of production or consumption of industrial products located in that specific basin is *at least 1%* of the total water footprint of production or consumption of industrial products; and (c) the contribution of industrial activities to the total blue water footprint in that specific basin in the period of scarcity is significant (*more than 5%*). In addition, a river basin is also identified as a priority basin if the following two conditions are met: (a) the water scarcity in the river basin is *severe* during part of the year; and (b) the contribution of industrial activities to the total blue water footprint in that specific basin in the period of scarcity is very significant (*more than 20%*).

In addition to the quantitative analysis to identify priority basins and products regarding the blue water footprint of French production and consumption, we assessed the impacts of the grey water footprint of French production and consumption on a qualitative basis.

4.3 Results

4.3.1 Water footprint of production

The total water footprint of national production in France is 90 Gm^3/year for the period 1996-2005, which is 1% of the total water footprint of production in the world (Hoekstra and Mekonnen, 2012a). The largest part of this water footprint is green (76%), followed by grey (18%) and blue (6%) (Table 4.1). Crop production constitutes the largest share (82%) in the water footprint of national production in France, followed by industrial activities (8%), grazing (6%), domestic water supply (3%) and livestock production (1%). Among the crops, cereals contribute 47% to the total water footprint. Fodder crops (15%), oil seed crops (9%) and fruits and nuts (6%) are the other major crop groups with a significant share in the total water footprint (Figure 4.2). Crop production contributes 50% to the total *blue* water footprint within France. The shares of industrial production, animal water supply and domestic water supply in the blue water footprint are 26, 14 and 11% respectively. In France, the grey water footprint is largely due to crop and industrial production.

Table 4.1. The water footprint of national production in France (Mm^3/year) by major category.

Water footprint of crop production			Water footprint of grazing	Water footprint of animal water supply	Water footprint of industrial production		Water footprint of domestic water supply		Total water footprint		
Green	Blue	Grey	Green	Blue	Blue	Grey	Blue	Grey	Green	Blue	Grey
62700	2849	8018	5672	778	1488	5654	628	2221	68372	5743	15894

The spatial distributions of the green, blue and grey water footprint of national production in France are shown in Figure 4.3. The water footprint per region is presented in Figure 4.4. Centre region has the largest water footprint with 9.6 Gm^3/year (12% of the total). Other regions with a significant share are Midi-Pyrenees (7.6 Gm^3/year), Poitou-Charentes (6.7 Gm^3/year), Champagne-Ardenne (5.5 Gm^3/year), Aquitaine (5.4 Gm^3/year), Pays de la Loire (5.3 Gm^3/year), Picardie (5 Gm^3/year), Bourgogne (4.7 Gm^3/year), and Rhone-Alpes (4.2 Gm^3/year). The largest *blue* water footprint in France is in Midi-Pyrenees (where 14% of the blue water footprint within France is located). Aquitaine, Ile-de-France, Centre, Poitou-Charentes, Pays de la Loire, Rhone-Alpes, Provence-Alpes-Cote d'Azur, Languedoc-Roussillon are other regions with a large blue water footprint. The largest *grey* water footprint in France is in Ile-de-France (where 10% of the grey water footprint within France is located), followed by Centre (8%), Midi-Pyrenees (7.8%), Rhone-Alpes (7.3%), Aquitaine (6.6%), Poitou-Charentes (6.4%), and Pays de la Loire (6%). The large grey water footprint in Ile-de-France is due to the high population and industrial activity in the region, especially near Paris metropolitan area.

The water footprint of agricultural production (crop production, grazing, and livestock water supply) in the period 1996-2005 was 80 Gm^3/year, which is 89% of the total water footprint in France. Wheat (29%), fodder crops (18%), maize (14%), barley (9%), rapeseed (7%), grapes (5%), sunflower (4%) and sugar beet (2%) are together responsible for 88% of the total agricultural water footprint. Cauliflower, artichokes, carrots, lettuce, asparagus, onions, cabbages and tomatoes are the major vegetables with large water footprints. Among the fruits, the water footprint of grapes is the largest, followed by apples, peaches and plumes.

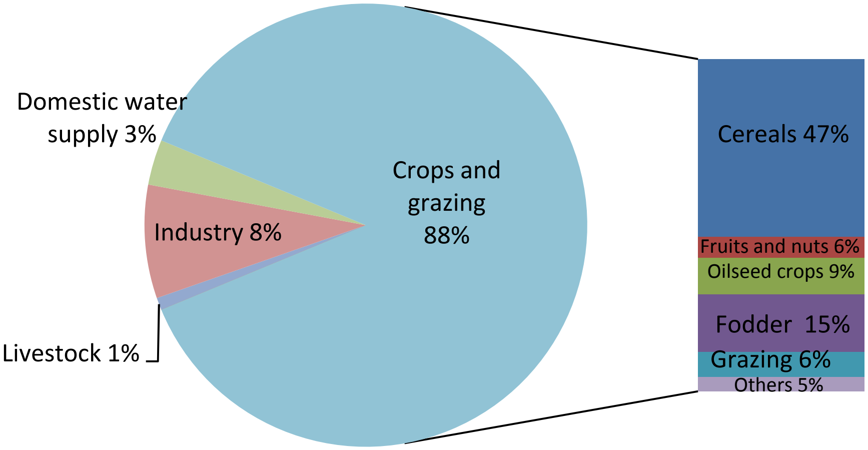

Figure 4.2. The water footprint of national production in France by sector.

Table 4.2. The water footprint of national production in France (Mm^3/year) in its major river basins.

River basin	Total related to agricultural production			Related to industrial production		Related to domestic water supply		Total water footprint*			
	Green	Blue	Grey	Blue	Grey	Blue	Grey	Green	Blue	Grey	Total
Loire	13868	606	1754	195	741	82	291	13868	884	2787	17538
Seine	12919	305	1531	389	1478	164	581	12919	858	3590	17367
Garonne	7113	746	1117	82	313	35	123	7113	863	1553	9530
Rhone	6325	329	729	221	836	94	332	6325	645	1896	8866
Rhine	3222	24	454	113	417	47	166	3222	184	1037	4444
Escaut	1256	24	161	58	221	24	86	1256	106	467	1829
Ebro	19	1	2	0	1	0	1	19	1	4	24
Po	5	0	0	0	2	0	1	5	1	3	9

* The water footprints within these major river basins sum up to 66 % of the total water footprint of production in France.

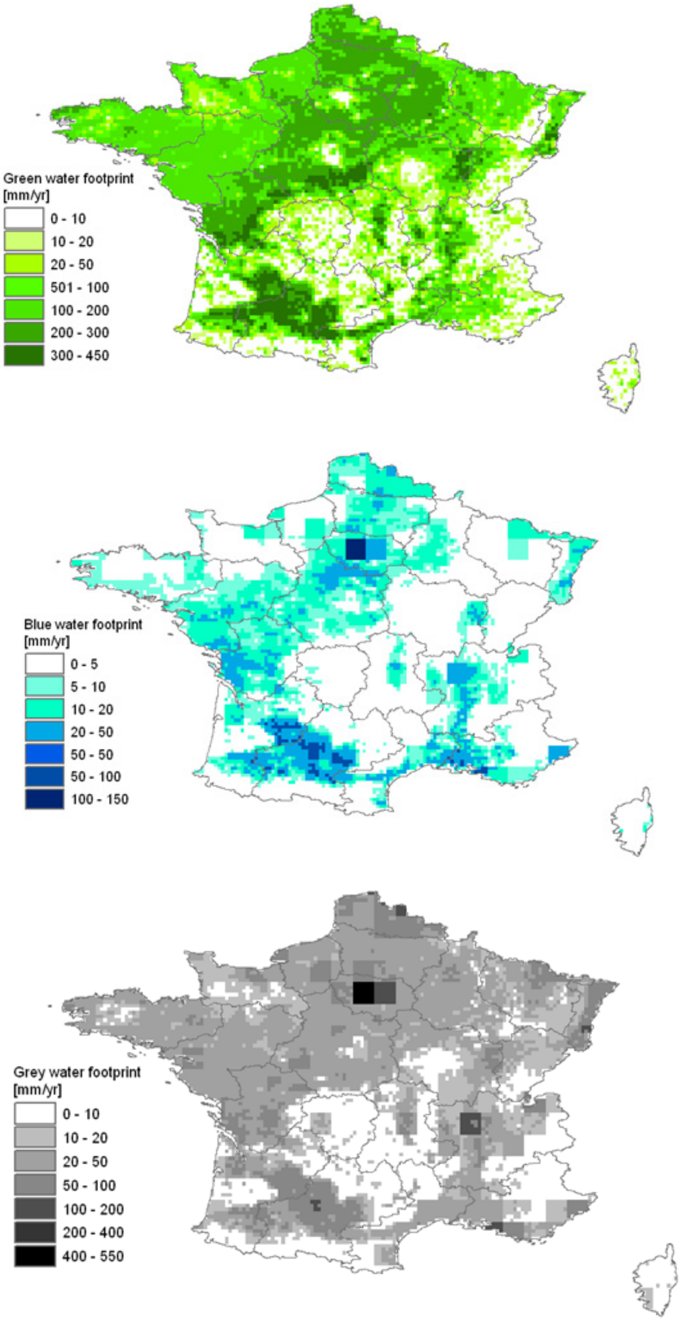

Figure 4.3. Spatial distribution of the green, blue and grey water footprint of production in France.

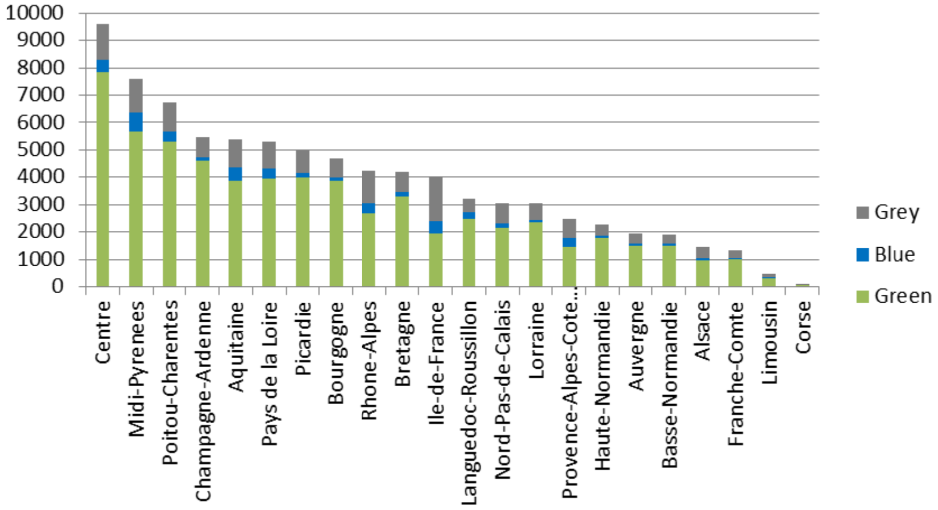

Figure 4 4. The green, blue and grey water footprint of national production per region in France (Mm^3/year).

Figure 4.5 shows the contribution of different crops to the green, blue and grey water footprint of total crop production in France. Maize production has the largest blue water footprint in France, and equals to the 50% of the total. Other crops with a significant share in the blue water footprint are fodder crops (6%), potato (4%), soybean (3%), rice (3%), and apples (2%). The green water footprint is mainly due to wheat production (34%), followed by fodder crops (19%), maize (10%), barley (9%), rapeseed (7%), grapes (6%), and sunflower (3%). The largest contribution to the grey water footprint comes from maize production (30%), followed by barley (18%), fodder crops (14%), sunflower (11%), rapeseed (9%), potato (4%) and sugar beet (3%).

The regional distribution of the water footprint related to agricultural production is shown in Figure 4.6. The largest agricultural water footprint (12.4% of the total) is in Centre region. Other regions with a relatively large agricultural water footprint are Midi-Pyrenees, Poitou-Charentes, Champagne-Ardenne, Aquitaine, Pays de la Loire, Picardie, Bourgogne and Bretagne. The largest blue water footprints related to crop production are located in Midi-Pyrenees, Aquitaine, Centre, Poitou-Charentes, Pays de la Loire, Languedoc-Roussillon, Provence-Alpes-Cote d'Azur and Rhone-Alpes. The largest part of the crop-related blue water footprint in France is due to maize production, which is located mainly in Midi-Pyrenees (23%), Aquitaine (19%), Poitou-Charentes (12%) and Centre (12%). The grey water footprint distribution among the regions is as follows: Centre (12%), Midi-Pyrenees (11%), Poitou-Charentes (10%), Aquitaine (9%), Champagne-Ardenne (7%), Pays de la Loire (6%), Picardi (6%) and Bourgogne (5%). The green water footprint distribution among the regions is similar to blue.

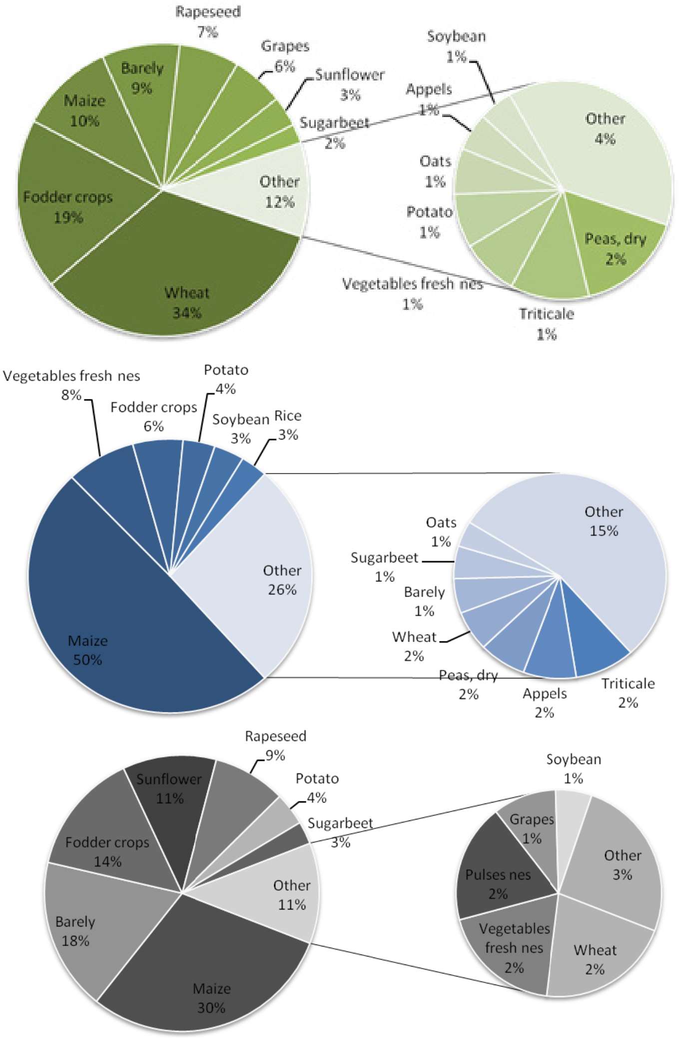

Figure 4.5. The contribution of different crops to the green, blue and grey water footprint of total crop production in France.

The water footprint of industrial production in France in the period 1996-2005 was 7.1 Gm^3/year. This footprint is dominated by the grey component (5.6 Gm^3/year), which represents the pollution due to industrial production. The water footprint of industrial production is concentrated in the Seine (26%), Rhone (15%), Loire (13%), Rhine (7%) and Garonne (6%) basins (Table 4.2). Ile-de-France, Rhone-Alpes, Provence-Alpes-Cote d'Azur and Nord-Pas-de-Calais are the regions where water footprint of industrial production is relatively large.

The water footprint of domestic water supply in France in the period 1996-2005 was 2.8 Gm^3/year. The majority of it is grey water footprint (78%). This water footprint is large where population concentrations are high and located mainly in Ile-de-France, Rhone-Alpes and Provence-Alpes-Cote d'Azurb. From a river basin point of view: the Seine, Rhone, Loire and Rhine basins, where most of the French population lives, have the largest water footprint related to domestic water supply.

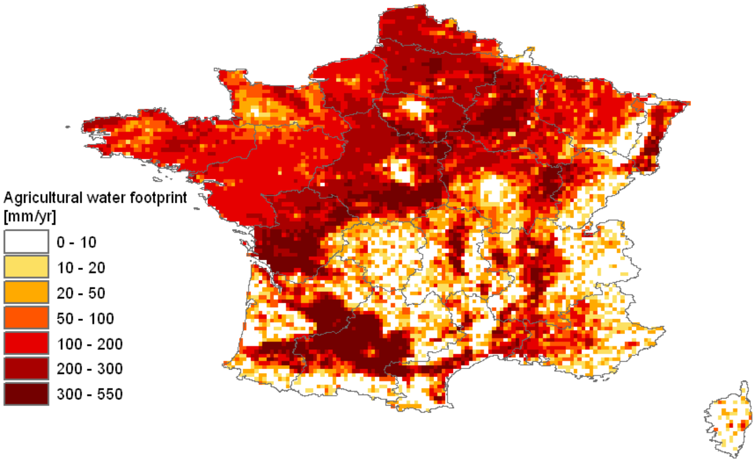

Figure 4.6. Spatial distribution of the water footprint of agricultural production in France.

4.3.2 Virtual water flows

The total virtual water import to France in the period 1996-2005 was 78.3 Gm^3/year. About 73% of the virtual water imports relates to imported crops and crop products, 15% to imported industrial products and 12% to imported animal products (Table 4.3). The largest share (22%) of the total virtual water import relates to the import of cotton and its derived products. Figure 4.7 shows the contribution of different products to the virtual water import, distinguishing between green, blue and grey virtual water imports.

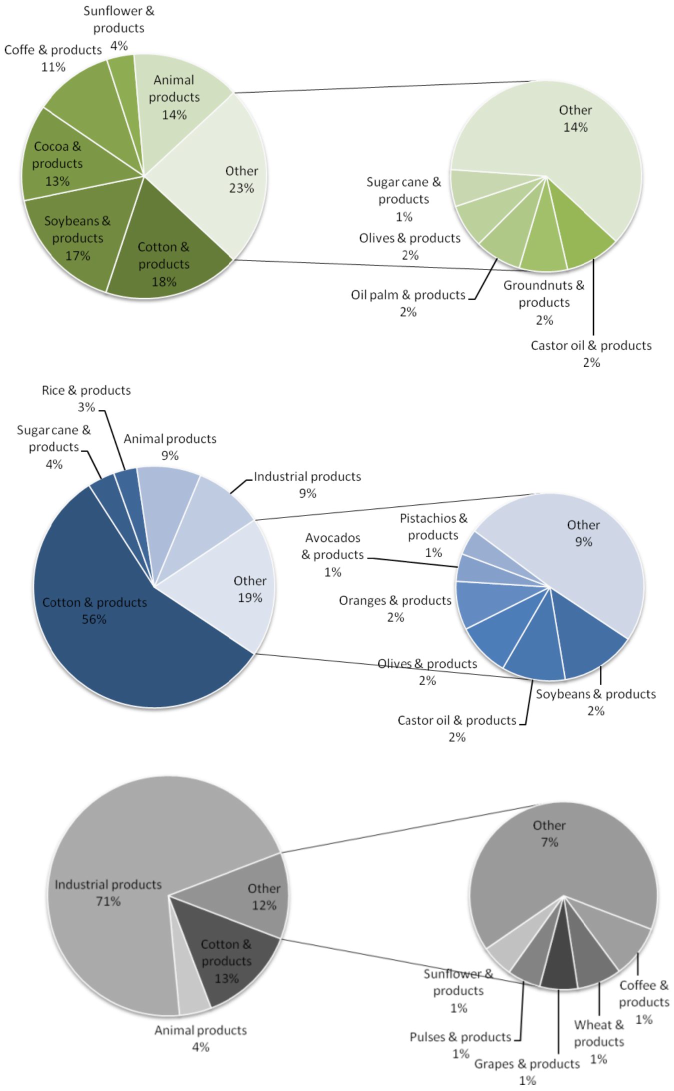

Figure 4.7. The green, blue and grey virtual water import to France by product group.

The green water footprint of imported products is 52.7 Gm^3/year and is 67% of total virtual water import. Cotton products have the largest green water footprint among the imported products, accountable for 18% of the total green virtual water import. Soybean products (17%), animal products (14%), cocoa products (13%) and coffee products (11%) are other products with a significant share in the green virtual water import. The blue water footprint of imported products in France is 10.5 Gm^3/year. Approximately 56% of this footprint is due to cotton products. Animal and industrial products also have significant shares in blue virtual water imports (9% each). The grey water footprint of imported products is 15.1 Gm^3/year. Industrial products give the largest contribution to this grey water footprint (71%), followed by cotton products (13%) and animal products (4%).

The majority of the virtual water imports to France originate from Brazil (10%), Belgium (9%), Spain (7%), Germany (7%), Italy (6%) and India (5%). Spain, Belgium, Morocco, Italy, India, Uzbekistan, and Turkey are the largest blue virtual water exporters to France, accounting for 55% of the blue virtual water import. The grey component of virtual water import is mainly from China (10%), Germany (10%), Russia (10%), Italy (7%), Belgium (7%), the USA (7%), Spain (5%) and India (4%). The green, blue and grey water footprints of virtual water imports to France are shown in Figure 4.8.

The blue water footprint related to the total of imported cotton products is mainly located in Uzbekistan, Turkey, India, Tajikistan, Turkmenistan and China. The blue water footprint related to imported animal products mainly lies in Spain, Belgium, the Netherlands, Germany and Italy. For industrial products, this ranking is: Germany (15%), the USA (11%), China (9%), Italy (8%) and Russia (8%). Most of the grey water footprint related to the import of industrial products lies in Russia (14%), China (11%), Germany (10%) and the USA (7%).

The total virtual water export from France in the period 1996-2005 was 65.5 Gm^3/year (Table 4.3). Since virtual water imports were larger than virtual water exports, France is a net virtual water importer. The virtual water export is dominated by export of crop products (69%) and followed by animal products (19%) and industrial products (12%). The largest part of the virtual water export concerns green water (70%). The blue and grey virtual water exports contribute 11 and 18% of total virtual water exports respectively.

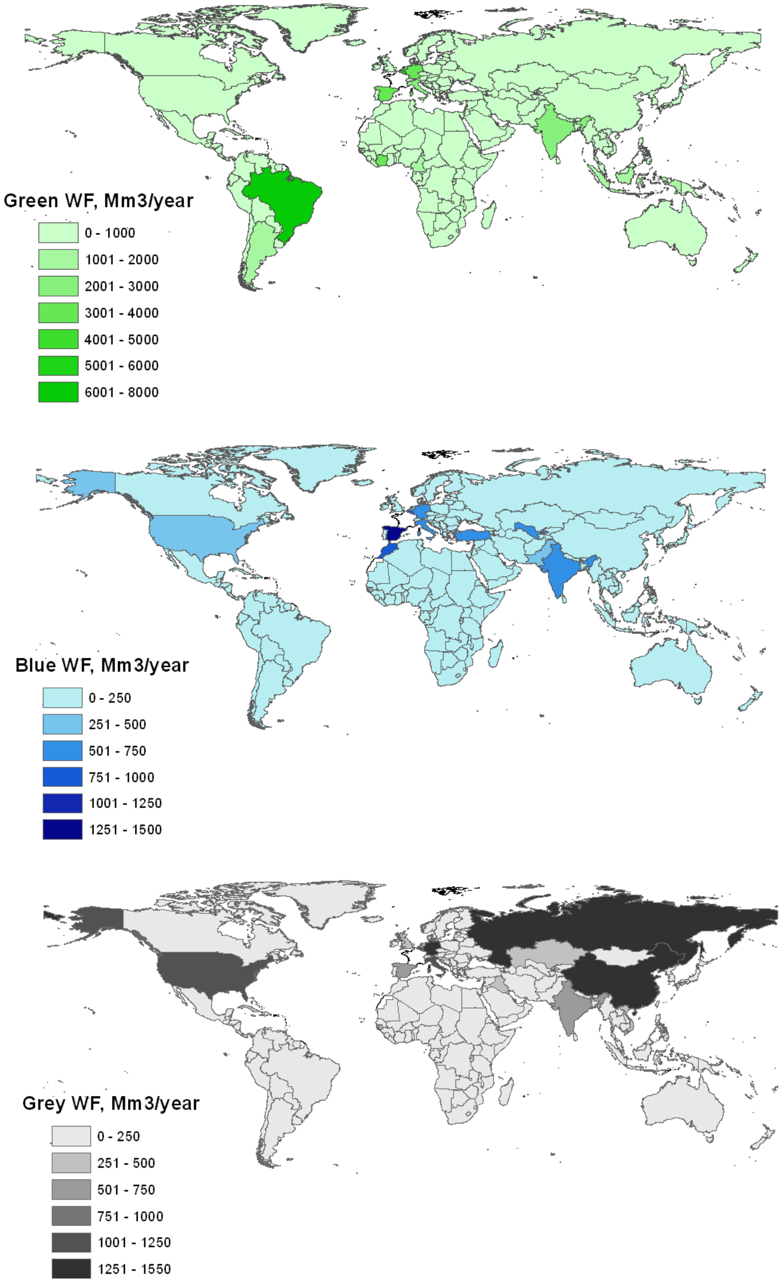

Figure 4.8. Spatial distribution of the green, blue and grey water footprint of total virtual water import to France.

Table 4.3. Virtual water import to France by product category (Gm^3/year).

	Crop products			Animal products			Industrial products		Total		
	Green	Blue	Grey	Green	Blue	Grey	Blue	Grey	Green	Blue	Grey
Import	45.1	8.6	3.8	7.6	0.9	0.6	1.0	10.7	52.7	10.5	15.1
Export	35.9	4.9	4.4	10.1	1.5	0.8	1.0	6.7	46.0	7.4	12.0

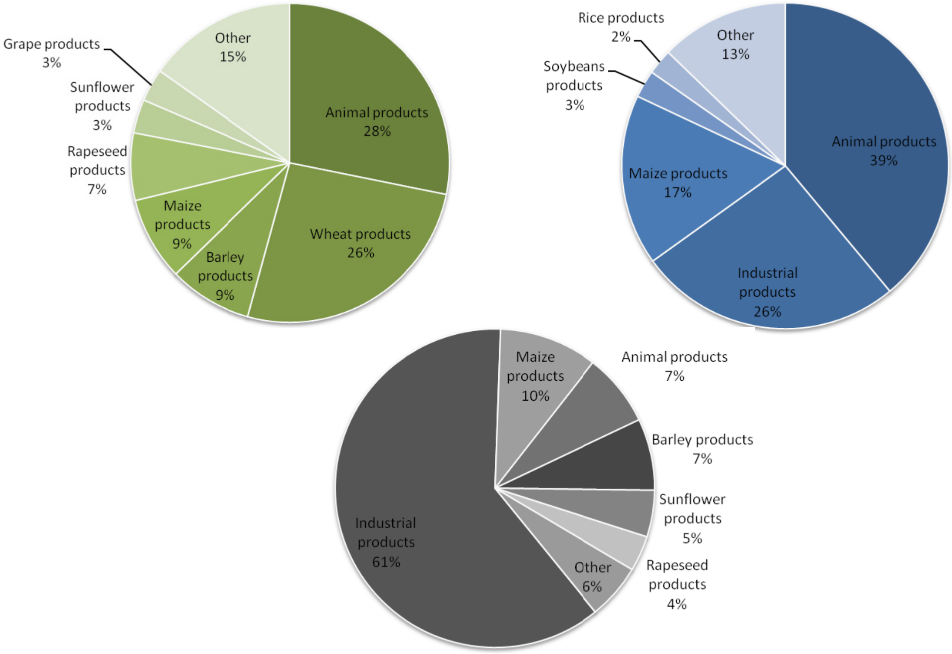

Figure 4.9. Green, blue and grey virtual water export from France by product group.

The largest virtual water flows leaving France go to Belgium (16%), Italy (13%), Germany (11%), Spain (8%), the United Kingdom (7%), the Netherlands (7%), Algeria (3%) and Libya (3%). Figure 4.9 shows the virtual water exports by product category. This figure only shows virtual water exports related to domestically made products. Animal and wheat products together are responsible for 54% of the green virtual water flows from France. Barley, maize, rapeseed, sunflower and grape products are other major commodities with a large share in green virtual water exports. Blue virtual water exports from France are mainly due to the export of animal products (39%), industrial products (26%) and maize products (17%). The largest grey virtual water export is due to the export of industrial products (61% of the total) and is followed by maize, animal and barley products.

4.3.3 Water footprint of consumption

The total water footprint of consumption in France is 106 Gm^3/year over the period 1996-2005. The green component is the largest and is equal to 76% of total water footprint of consumption. Blue and grey water footprints of national consumption are 8 and 17% of the total. About 53% of the water footprint of French national consumption is internal and 47% is external (Table 4.4). This means that nearly half of the water resources consumed or polluted to make all products consumed by French citizens are water resources outside the country.

The largest fraction (87%) in the total water footprint of French consumers relates to the consumption of agricultural products. Consumption of industrial products and domestic water supply contribute 10% and 3% to the total water footprint of consumption, respectively (Table 4.5). The internal water footprint of French consumption is mainly because of the consumption of agricultural products, followed by industrial products and domestic water supply (Figure 4.10). The external water footprint is largely due to the import of agricultural products for domestic consumption, and for a smaller part due to the import of industrial products. The ratio of external to total water footprint of consumption is higher for industrial products (62%) than for agricultural products (47%). Furthermore, the ratio of external to total water footprint is significantly higher for the blue water footprint (64%) than for the green water footprint (46%) or the grey water footprint (47%). For agricultural products, even 77% of the total blue water footprint of consumption is external.

Table 4.4. The internal and external water footprint of French consumption (Mm^3/year).

Internal water footprint			External water footprint			Total water footprint			Ratio of external to total water footprint (%)
Green	Blue	Grey	Green	Blue	Grey	Green	Blue	Grey	
43704	2879	9295	36739	5156	8355	80443	8036	17649	47

Table 4.5. The water footprint of French consumption per major consumption category (Mm^3/year).

Water footprint of consumption of agricultural products						Water footprint of consumption of industrial products				Water footprint of domestic water supply	
Internal			External			Internal		External			
Green	Blue	Grey	Green	Blue	Grey	Blue	Grey	Blue	Grey	Blue	Grey
43704	1375	3753	36739	4577	2078	876	3320	579	6277	628	2221

With a contribution of 34%, meat consumption is the largest contributor to the total water footprint of French consumption (Figure 4.11). Industrial products (10%), coffee, tea and cocoa (9%), and milk (9%) are other large contributors. The consumption of cereals and sugar contribute 5% and 4% to the total water footprint of consumption, respectively. Rubber, fruits, wine & beer, and domestic water supply each have a 3% share in the total water footprint of consumption. Meat, coffee-tea-cocoa, milk, vegetable oils and cereals have the largest shares in the total *green* water footprint of French national consumption (40, 12, 10, 7 and 6% respectively). The *blue* water footprint is also dominated by meat consumption (23%). Consumption of industrial products (18%), fruits (8%), milk (8%) and domestic water supply (8%) are other sectors with a large share in the total blue water footprint. The *grey* water footprint of consumption is mainly due to the consumption of industrial products (54%), followed by domestic water supply (13%), meat (12%) and milk (5%).

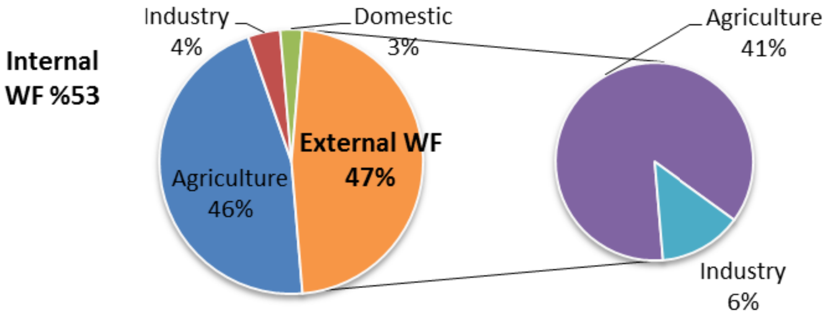

Figure 4.10. The total water footprint of French consumption shown by internal and external component.

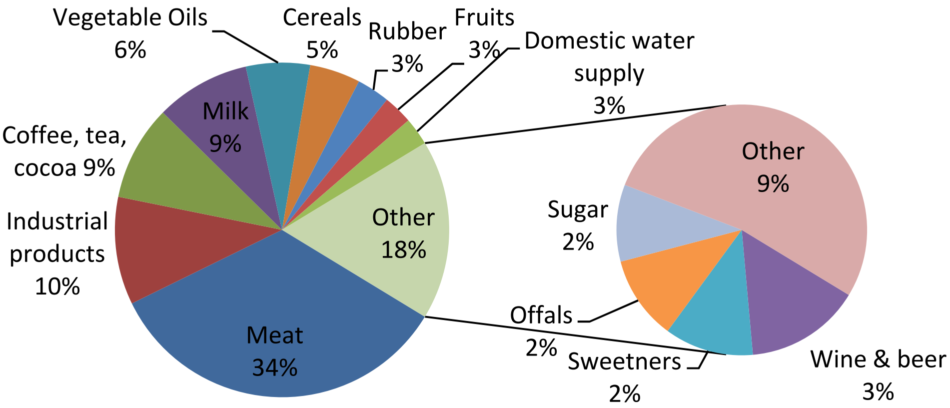

Figure 4.11. The total water footprint of French consumption shown by consumption category.

When we compare the external water footprint of France to virtual water imports, we see that some part of the virtual water imports to France is not consumed domestically. Around 35% of the virtual water import is re-exported again. Part of the re-export of virtual-water is done after having processed imported raw materials. A typical example of such processing is related to cotton and cocoa products. Crops are imported from Asia and Latin America to be used as an input to textile and cocoa industries. When we compare the internal water footprint of French consumption to the water footprint of production within France, we see that the latter is much bigger. About 60% of the total water footprint of production in France is for domestic consumption. The rest of the water footprint in the country is for the production of export commodities.

The geographic distribution of the water footprint of consumption by French citizens is shown in Figure 4.12. More than 50% of the external water footprint of French consumption comes from Brazil, Belgium, Spain, Germany, Italy, India and the Netherlands. The geographic spreading of the external water footprint related to the consumption of agricultural and industrial products are different from each other. The external agricultural water footprint is mainly from Brazil, Belgium, India, Spain, and Germany, while the external industrial water footprint is more concentrated in China, Russia, Germany and the USA.

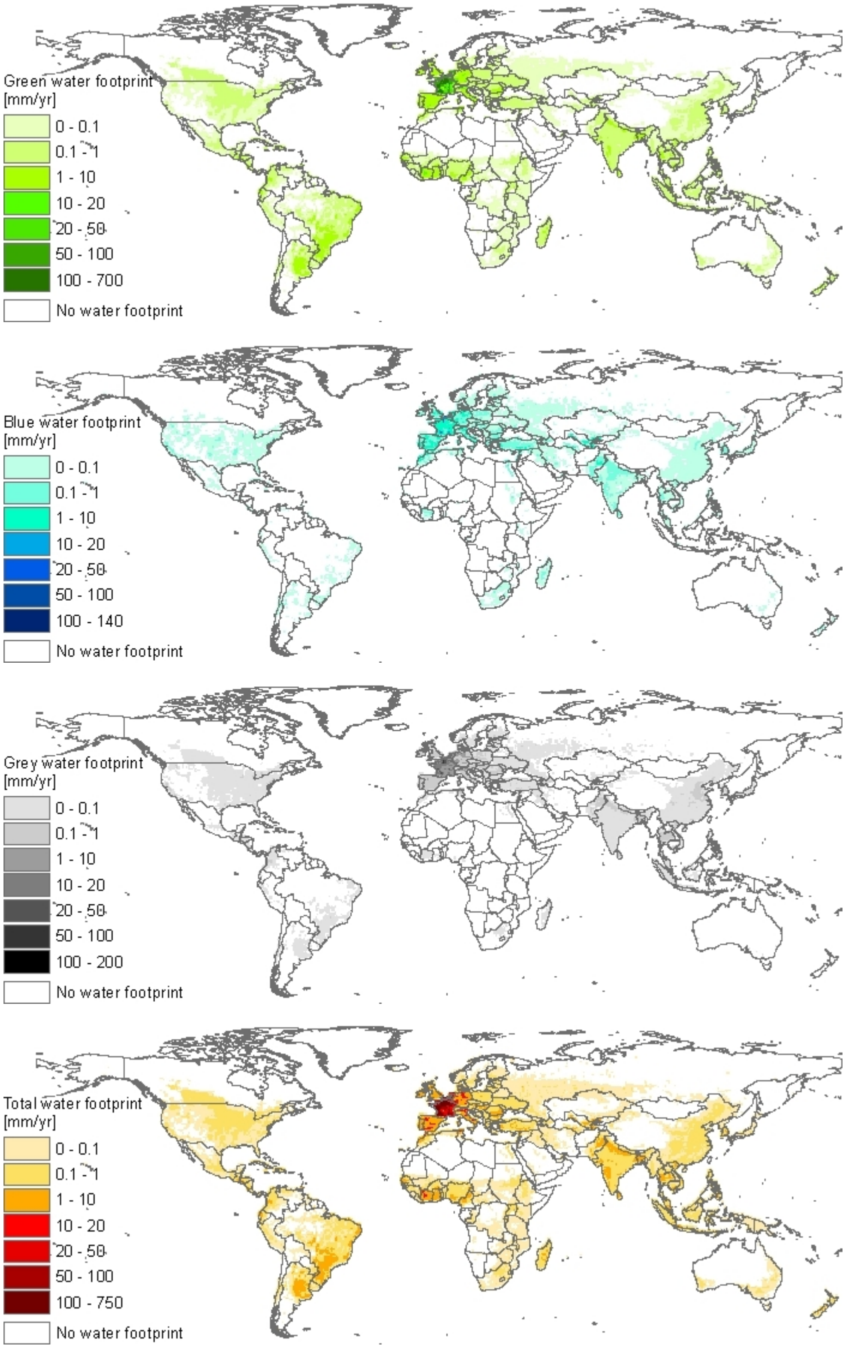

Figure 4.12. The global water footprint of consumption by the inhabitants of France (period 1996-2005).

The water footprint of a consumer in France in the period 1996-2005 was, on average, 1786 m^3/year (Table 4.6). Compared to other EU countries, the water footprint of consumption per capita in France is below the average. However, it is more than the world average, which is 1385 m^3/year (Figure 4.13). Countries like Portugal, Spain, Cyprus and Greece have very large water footprints per capita, whereas the UK and Ireland have the smallest water footprints per capita in Europe. As can be seen from Figure 4.14, the water footprint of consumers in Europe is dominated by agricultural products. The share of industrial products is especially high in countries like Belgium, Luxembourg and Switzerland.

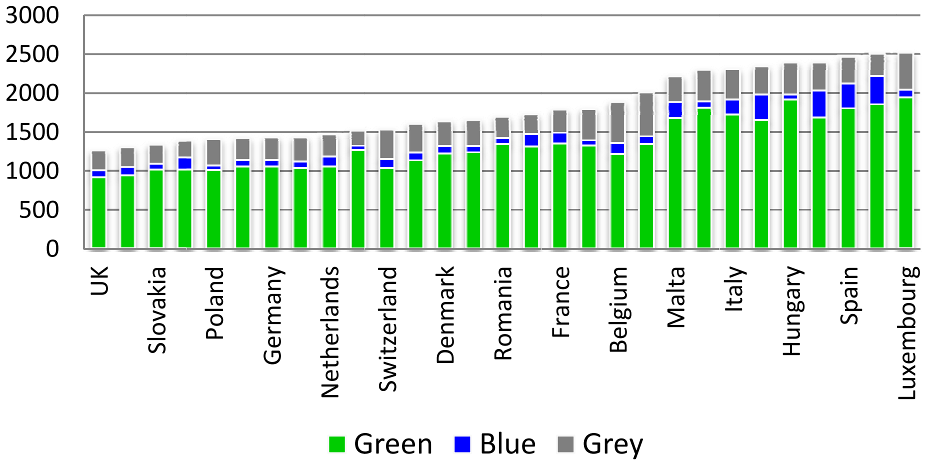

Figure 4.13. The green, blue and grey water footprint of consumption per capita in EU countries and the world average (m^3/year/cap).

Table 4.6. The water footprint of French consumption per capita (m^3/year/cap).

Population (thousands)	Internal water footprint			External water footprint			Total water footprint			
	Green	Blue	Grey	Green	Blue	Grey	Green	Blue	Grey	Total
59436	735	48	156	618	87	141	1353	135	297	1786

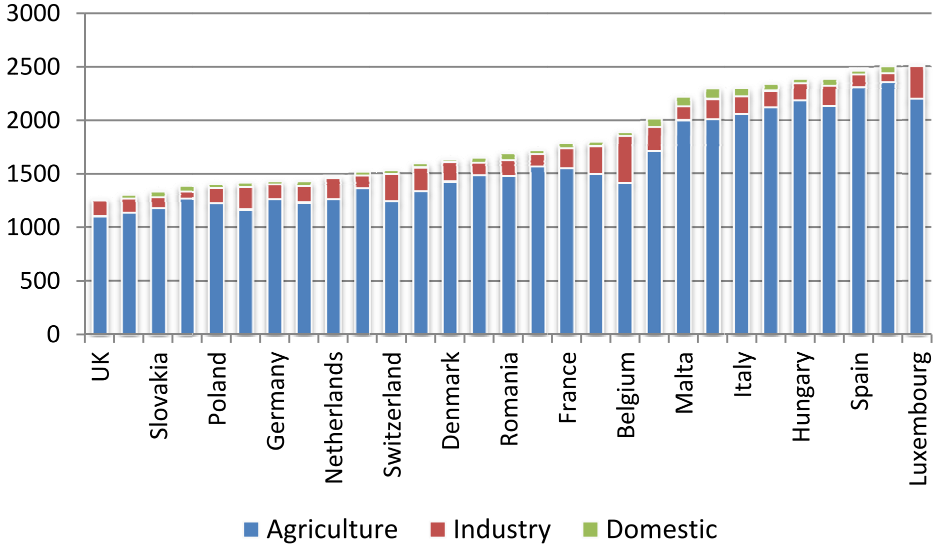

Figure 4.14. The water footprint of consumption per capita per consumption category in EU countries and the world average (m^3/year/cap).

4.4 Priority basins and products

4.4.1 Water footprint of production

As described in Section 4.3, the blue water footprint of France is dominated by crop production and followed by industry and domestic water supply. The blue water footprint is mainly located in the Loire, Seine, Garonne, Rhone, Rhine and Escaut river basins. Four of these basins – the Loire, Seine, Garonne and Escaut – experience moderate to severe water scarcity at least one month a year. Table 4.7 shows, for each of these four basins, the months in which the moderate to severe water scarcity occurs and the products that dominate the water footprint in these months. The Loire, Seine and Garonne basins have the largest shares in the blue water footprint of production in France, 15% each. The blue water footprint in the Escaut basin is much smaller, but the area of this basin is also much smaller than for the other three basins (Figure 4.15).

Table 4.7. Priority basins regarding the blue water footprint of production in France.

River basin	Month	Level of scarcity	Products with significant contribution to the blue water footprint in the basin (% of contribution)
Loire	August	Significant	Maize (58%), industrial production (6%)
	September	Significant	Maize (45%), industrial production (10%)
Seine	July	Moderate	Industrial production (28%), maize (18%), domestic water supply (12%), potato (11%)
	August	Severe	Maize (38%), industrial production (21%), domestic water supply (9%), potato (%7), sugar beet (%6)
	September	Severe	Industrial production (28%), maize (27%), domestic water supply (12%)
	October	Moderate	Industrial production (5 %), domestic (24%)
Garonne	July	Moderate	Maize (54%), soybean (1 %), fodder (5%)
	August	Significant	Maize (59%), soybean (7%)
	September	Severe	Maize (69%), soybean (8%)
Escaut	July	Significant	Industrial production (61%), domestic water supply (17%), potato (10%)
	August	Severe	Industrial production (57%), domestic water supply (16%), maize (10%), potato (8%)
	September	Severe	Industrial production (70%), domestic water supply (20%)
	October	Severe	Industrial production (77%), domestic water supply (22%)

The Loire river basin experiences significant water scarcity in August and September. The main activities contributing to the blue water footprint in this basin are maize and industrial production. The Loire basin is considered an important farming area, producing two thirds of the livestock and half of the cereal produced in France. The banks of the river offer a habitat for a rich biodiversity. The river is a refuge for European beavers, otters, and crested newts, and a migration route for fish such as Atlantic salmon. The decrease in water levels in the river during the summer period has a negative effect on the biodiversity located in the banks of the river (UNEP, 2004).

The Seine and Escaut river basins experience water scarcity from July to October. The blue water footprint during this period in these basins is mainly because of industrial production, domestic water supply, and maize and potato production. The Seine river passes through Paris; the high level of urbanization and industrialization has a major impact on the water quality in the basin. Pollution is due to industrial and domestic wastewater, but also intensive agriculture. Agricultural production has a big impact on water quality because it favours intensive farming techniques and spring crops, which leave the soil bare for long periods of the year and increase the chemical load in the rivers by leaching and draining. This has a harmful effect on both the environment and other water uses. Improving water quality is still the major concern of the basin, where non-point source pollution from farming and urban areas is still a major problem, as nitrate, pesticide and heavy metal concentrations continue to increase (UNEP, 2004).

The Garonne faces moderate to severe water scarcity in the period from July to September. The production of maize is the dominant factor behind the blue water scarcity in this basin. Soybean and fodder are two other products that contribute significantly to the blue water footprint in the basin. The Garonne is the most important river of south-western France and main water source for five major cities, including Bordeaux. The Bordeaux region is known for its industrial activities and is well known for the quality of its vineyards. The region especially experiences water shortages during summertime (UNESCO, 2006; AEAG, 2011). The Garonne is an important breeding area for sturgeon and for the migration of Atlantic salmon. Its estuary, in particular, is a very important site for fish and bird migrations. The water quality is worsening with wastewater from the city of Bordeaux, causing high levels of nitrogen and phosphorous concentrations downstream of Bordeaux. One tributary of the Garonne, the Dropt, is particularly sensitive to eutrophication (Devault et al., 2007; UNEP, 2004). The pollution of a few heavy metals is observed in the Garonne due to industrial activities, especially mining in the basin. This contamination is considered as critical because of the sensitivity of the marine ecosystems located at the downstream (Grousset et al., 1999).

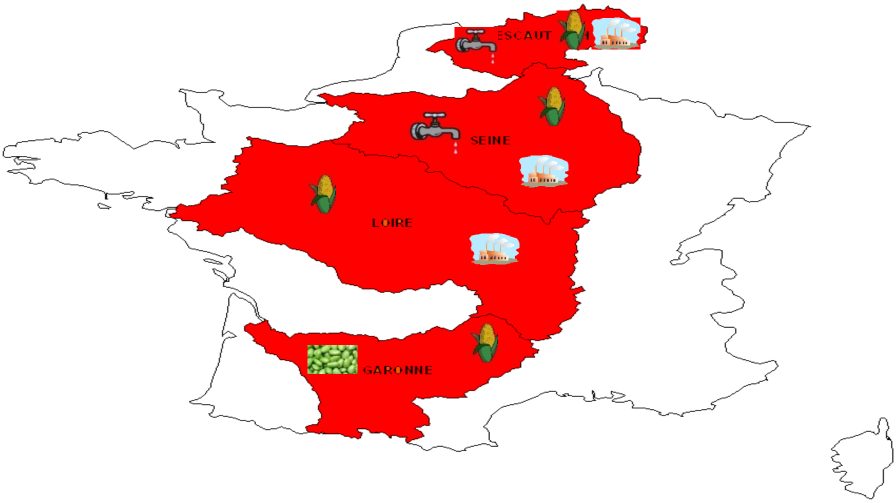

Figure 4.15. Priority basins and products regarding the blue water footprint of production in France.

A significant portion of the blue water footprint of production in France is for production of export commodities. Around 60% of the agricultural blue water footprint and 40% of the industrial blue water footprint of production are not for producing commodities for internal consumption but for production of export goods. Therefore, some of the impacts of the water footprint of production in French river basins are due to consumption happening elsewhere in the world but not in France.

4.4.2 Water footprint of consumption

The blue water footprint of French consumption is partly within France and partly outside. In many of the basins where part of the water footprint of French consumption is located, water scarcity is beyond hundred per cent during part of the year.

<u>Agricultural products</u>. We will focus first on the water footprint of French consumption of agricultural products. Table 4.8 presents the river basins across the globe where there is a significant blue water footprint related to French consumption of agricultural products and where there is moderate, significant or severe water scarcity during part of the year. A 'significant' blue water footprint in a basin means here that at least 1% of the blue water

footprint of French consumption of agricultural products is located in this basin. The table 4.8 also shows a list of river basins where less than 1% of the blue water footprint of French consumption of agricultural products is located. In these basins, water scarcity is severe during part of the year (or even the full year) and the contribution of one or more specific agricultural commodities to the total blue water footprint in the basin in the period of severe scarcity is very significant (more than 20%). Although France imports this or these products in relative small amounts (less than 1% of the blue water footprint of French consumption of agricultural products is located in those basins), these products are obviously contributing to very unsustainable conditions. Table 4.8 shows, per basin, the number of months per year that the basin faces moderate, significant or severe water scarcity, and priority products per basin. These priority products are the products that contribute significantly to the basin's blue water scarcity and are imported by France. The basins listed in Table 4.8 are shown on the world map in Figure 4.16.

The Aral Sea basin is identified as one of the most important priority basins, since 6% of the blue water footprint of French consumption of agricultural products is located there. The basin experiences one month of moderate water scarcity (June) and four months of severe water scarcity (July to October). Cotton production is the dominant factor in the blue water scarcity of the basin (more than 50%). Next in line of the priority basins are the four French river basins that were already identified in the previous section as well: the Garonne, Loire, Escaut and Seine basins. The blue water footprints within those basins lead to moderate to severe water scarcity during parts of the year. For an important part, the blue water footprints of production in these basins relate to producing for the domestic market. A sixth priority basin is the Indus basin, in which 4% of the blue water footprint of French consumption of agricultural products is located. The basin faces severe water scarcity during eight months of the year. The blue water footprint in the Indus basin is mainly due to wheat, cotton, rice and sugar cane production. However, wheat is not one of the products that France imports from Pakistan, thus it is not a product of major concern for French consumers.

Table 4.8. Priority basins regarding the blue water footprint of French consumption of agricultural products.

River basin	Percentage of the blue WF of French consumption of agricultural products located in this basin	Number of months per year that a basin faces moderate, significant or severe water scarcity			Major contributing products
		Moderate	Significant	Severe	
Aral Sea basin	6.4	1	0	4	Cotton
Garonne	5.4	1	1	1	Maize, soybean, animal products
Escaut (Schelde)	4.5	0	1	3	Maize, potato
Loire	4.4	0	2	0	Maize
Indus	3.9	1	3	8	Cotton, rice, sugar cane
Guadalquivir	3.0	1	0	6	Cotton, sun flower, rice, sugar beet
Seine	2.2	2	0	2	Maize, potato, sugar beet
Ganges	2.2	0	2	5	Rice, sugar cane
Guadiana	1.8	1	0	6	Grapes, sunflower, citrus
Tigris & Euphrates	1.6	0	1	5	Cotton, rice
Po	1.6	2	0	0	Rice, animal products
Ebro	1.4	0	0	3	Maize
Sebou	1.4	1	1	5	Sugar beet
Douro	1.3	2	0	3	Maize, sugar beet
Tejo	1.0	1	0	4	Grapes, maize, animal products
Mississippi	0.60	2	0	2	Maize, soybean, rice, cotton
Krishna	0.45	1	1	7	Rice, sugar cane
Godavari	0.31	2	0	5	Rice, sugar cane
Kizilirmak	0.27	1	2	2	Sugar beet
Chao Phraya	0.26	2	1	4	Rice, sugar cane
Sakarya	0.25	0	1	5	Sugar beet
Bandama	0.21	0	0	2	Sugar cane, animal products
Cauvery	0.19	3	1	8	Rice, sugar cane
Yongding He	0.12	0	0	12	Cotton, soybean
Limpopo	0.11	2	0	5	Sugar cane, cotton
Sacramento	0.10	1	0	5	Rice
San Joaquin	0.10	1	0	7	Cotton, maize
Sassandra	0.08	0	0	2	Sugar cane
Comoe	0.08	0	0	2	Sugar cane
Tapti	0.07	2	1	5	Cotton, sugar cane
Murray	0.06	2	0	6	Sugar cane, cotton, rice
Penner	0.04	1	2	9	Rice
Incomati	0.03	1	0	3	Sugar cane
Tugela	0.02	2	0	3	Grape, animal products
Doring	0.01	0	1	7	Sugar cane, grapes
Nueces	0.01	0	0	12	Maize

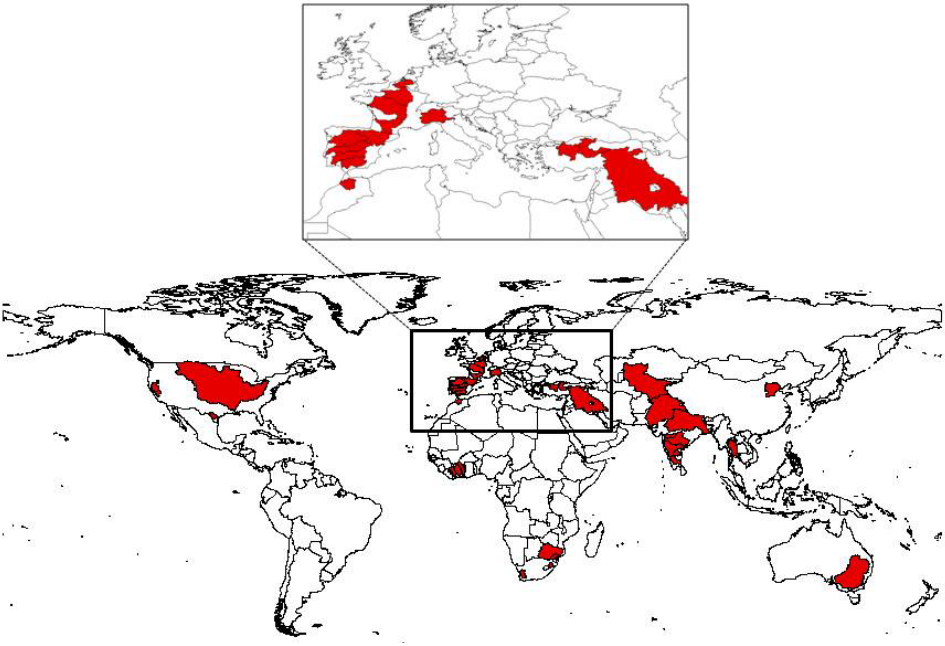

Figure 4.16. The river basins in the world in which the production of agricultural products for French consumption contributes to moderate, significant or severe blue water scarcity.

The Ganges, Krishna, Godavari, Cauvery, Tapti and Penner basins are river basins in India that are identified as priority basins. All these basins experience severe water scarcity during most of the year. Rice and sugar cane production are the major reasons of blue water scarcity in these basins. The Guadalquivir, Guadiana, Douro and Tejo are Spanish-Portuguese river basins in which the blue water footprint of French consumption is significant. Sugar beet, maize, grapes, citrus and sunflower are the products that are imported by France and contribute largely to the blue water footprint in these basins.

As can be seen from Table 4.8, mainly eight agricultural products of concern are identified in 36 different priority basins: cotton, rice, sugar cane, sugar beet, soybean, maize and grape. Among them, cotton, sugar cane and rice are the three major crops. They have the largest share in the external blue water footprint of French consumption and are identified as products of concern in most of the priority basins. Therefore, we examined impacts of these three products in some of the identified priority basins in detail.

Cotton. Cotton is probably the most important product if it comes to the contribution of French consumers to blue water scarcity. French cotton consumption relates to blue water scarcity in a number of basins throughout the world: the Aral Sea basin (Uzbekistan), the Indus (Pakistan), the Guadalquivir (Spain and Portugal), the Tigris & Euphrates (originating in Turkey and ending in Iraq), the Mississippi (USA), the Yongding He (China), the Limpopo (South Africa), the San Joaquin (USA), the Tapti (India), and the Murray (Australia). The Aral Sea ecosystem has been experiencing sudden and severe ecosystem damage due to excessive water abstractions from the inflowing rivers to irrigate cotton fields and other export crops. This unsustainable use of water has environmental consequences, including fisheries loss, water and soil contamination, and dangerous levels of polluted airborne sediments. The impacts of extensive irrigation in the Aral Sea basin has extended far beyond the decline of the sea water level: millions of people lost access to the lake's water, fish, reed beds, and transport functions. Additionally, environmental and ecological problems associated with extensive water use for irrigation negatively affected human health and economic development in the region (Cai et al., 2003; Glantz, 1999; Micklin, 1988). Another well-documented case is the Murray basin in Australia, where water levels have declined significantly, particularly due to water abstractions for irrigation. Much of its aquatic life, including native fish, are now declining, rare or endangered (Chartres and Williams, 2006).

Sugar cane. Sugar cane is the second product if it comes to the contribution of French consumers to blue water scarcity in the world. Sugar cane consumed in France contributes to water scarcity in the following priority basins: the Indus (Pakistan), the Ganges (India), the Krishna (India), the Godavari (India), the Chao Phraya (Thailand), the Bandama (Côte d'Ivoire), the Cauvery (India), the Limpopo (South Africa), the Sassandra (Côte d'Ivoire), the Comoe (Côte d'Ivoire), the Tapti (India), the Murray (Australia), the Incomati (South Africa) and the Doring (South Africa). The freshwater reaching to Indus delta has significantly decreased (90%) as a result of over-usage of water sources in the Indus basin. Sugar cane is one of the main water consuming agricultural products in the basin. The decrease in freshwater flow to the Indus delta has negative impacts on the ecosystems and biodiversity of the delta (such as decrease of mangrove forestlands and danger of extinction of the Blind River Dolphin). Additionally, excessive water usage in sugar cane cultivation areas has led to salinity problems (WWF, 2004). Moreover, untreated wastewater discharge from sugar mills causes depletion of available oxygen in water sources, which threatens fish and other aquatic life (Akbar and Khwaja, 2006). India is also facing environmental problems due to sugar cane cultivation. In the Indian state of Maharashtra, sugar cane irrigation is 60% of the total irrigation supply, which causes substantial groundwater withdrawals (WWF, 2004). India's largest river, the Ganges, experiences severe water scarcity. Sugar cane is one of the major crops cultivated in the area and deteriorates the water scarcity. Another problem resulting from sugar cane cultivation and sugar processing activity in India is the pollution of surface and groundwater resources (grey water footprint) (Solomon, 2005).

Rice. Rice has the third largest share in the external blue water footprint of French consumption. In the following priority basins, rice is identified as one of the major products contributing to blue water scarcity: the basins of the Indus (Pakistan), Guadalquivir (Spain), Ganges (India), Tigris & Euphrates (Turkey to Iraq), Mississippi (USA), Krishna (India), Godavari (India), Chao Phraya (Thailand), Cauvery (India), Sacramento (USA) and Murray (Australia). The Guadalquivir is Spain's second longest river. Its natural environment is one of the most varied in Europe. Its middle reaches flow through a populous fertile region where its water is used extensively for irrigation. The lower course of the Guadalquivir is used for rice cultivation. In recent years, mass tourism and intensive irrigated agriculture in the region are causing over-exploitation of regional aquifers, which damages the ecosystem of the region (UNEP, 2004). The Guadalquivir marshes are negatively affected due to agricultural activities. The Guadalquivir is classified as one of the rivers in Europe mostly polluted due to non-point source emissions from agricultural activities (nitrate and phosphate) (Albiac and Dinar, 2008).

Industrial products. There are two river basins that face moderate to severe water scarcity during part of the year and where more than 1% of the blue water footprint of French consumption of industrial products is located: the Seine and the Escaut basins (Table 4.9). There are seven river basins where this contribution is smaller, but that can be classified as priority basin for another reason. These river basins are the basins of the Volga, St. Lawrence, Ob, Wisla, Don, Yongding He and Colorado. In these basins, water scarcity is severe during part of the year or even the full year, as in the case of the Yongding He (Table 4.9). Although France imports industrial products from these basins in relative small amounts (less than 1% of the blue water footprint of French consumption of industrial products is located in those basins), these products contribute to very unsustainable conditions because industrial products contribute more than 20% to the total blue water footprint in the basin in the period of severe scarcity.

Table 4.9. Priority basins regarding the blue water footprint of French consumption of industrial products.

River basin	Percentage of the blue water footprint of French consumption of industrial products located in this basin	Number of months per year that a basin faces moderate, significant or severe water scarcity		
		Moderate	Significant	Severe
Seine	5.5	2	0	2
Escaut (Schelde)	1.5	0	1	3
Volga	0.43	0	0	1
St. Lawrence	0.31	0	0	1
Ob	0.23	1	0	1
Wisla	0.14	0	0	1
Don	0.10	0	2	2
Yongding He	0.09	0	0	12
Colorado (Caribbean Sea)	0.01	1	0	6

Industrial products contribute to pollution as well. France’s industrial grey water footprint is located mainly in the Seine, Loire, Rhone, Escaut, Garonne, Volga, Mississippi, Po, St. Lawrence, Tigris & Euphrates, Ob, Huang He (Yellow River) and Yangtze basins.

China's longest river, the Yangtze, has been severely polluted. The surface water pollution in the river includes industrial and domestic sewage, animal manures, chemical fertilizers from farmlands, and polluted sediments. The Yellow River in China is known for pollution problems as well. According to Chinese government estimates, around two-thirds of the Yellow River's water is too polluted to drink. Around 30% of fish species in the river are believed to have become extinct and the river's fish catch has declined by 40% (Fu et al., 2004).

4.5 Discussion and conclusion

This study of the water footprint of national production and consumption for France is more detailed than previous national water footprint studies (that were carried out for other countries). It builds on the high-resolution global water footprint study by Hoekstra and Mekonnen (2012a) by zooming in on one particular country. The availability of the global study enabled us to map in a relatively precise way the external water footprint of French consumption. The study could make use of another recent study on global blue water scarcity (Hoekstra et al., 2012) to identify which parts of the French external water footprint are located in river basins that experience moderate to severe blue water scarcity during part of the year. The data that are thus generated can play a role in revisiting French national water policy. Linking specific consumer products in a country to water problems elsewhere is still uncommon in governmental thinking about water policy. Making this link visible can help in setting priorities in either national or international context with respect to the most effective measures to reduce water footprints in the basins where most needed. The study addresses questions like: where and when water footprints are largest, where and when they contribute most to local water scarcity and which specific products contribute most to water footprints and water scarcity? By making the links between specific consumer products and water problems visible, the study suggests that consumer product policy can be part of a water policy. The extent to which French government is willing to promote water footprint reductions in water-scarce basins and periods of the year through product-oriented policies is obviously a political question. This study shows how a political debate on this topic could be informed by relevant knowledge on how different products contribute to water scarcity.

Even though the study applies higher spatial and temporal resolutions than previous national water footprint studies, there are still limitations regarding the spatial and temporal detail, which primarily relate to lacking crop and irrigation data on even higher resolutions and to the problem of tracing supply chains and trade flows. One limitation in the study is that the origin of virtual water imports and the external water footprint of consumption have not been traced further than the first tier trade partners. If a product is imported from a country, we assume that the product has been produced in that country and we take the water footprint of the imported product accordingly. Another limitation related to trade data is that the origins of imported commodities are available on country level and not specified as per river basin or in even more geographic detail. In this study, we assumed that an imported product originates from the various river basins within the country proportionally to the production of that product in the various basins.

Another limitation in the study pertains to the problem of distinguishing between different industrial products. Different crop and animal products have been considered separately, but industrial commodities are treated as one product group. In future studies it would be worth trying to analyse different industrial sectors and commodities separately; currently, the major challenge still is the lack of water consumption and pollution data per industrial sector and the complexity of supply chains for many industrial commodities.

In this study, identification of priority river basins and priority products from the perspective of water resource use has been done primarily on the basis of data on the levels of blue water scarcity through the year on a river basin level. More precise results would be obtained if we could use water scarcity data on a finer spatial resolution level, for example at the level of sub-catchments. Especially for identifying hotspots within large river basins, this would be very helpful. Furthermore, by looking at 'blue water scarcity' from an environmental point of view, we may have neglected social issues of water conflict. For obtaining a more complete overview of potential critical basins and products, it would be helpful to look at other indicators than environmental water scarcity alone. It should further be noted that the blue water scarcity estimates used in this study (from Hoekstra and Mekonnen, 2011; Hoekstra et al., 2012) excluded the evaporation from storage reservoirs and the effect of inter-basin water transfers. This may result in an underestimation of blue water scarcity in basins with significant evaporation from large reservoirs and export of water to another basin and an overestimation of water scarcity in basins that receive significant volumes of water from another basin. The water scarcity estimates also exclude storage effects of large dams, which means that water scarcity may have been underestimated in periods of the year in which water is being stored and overestimated in periods of the year in which the water is being released. Finally, we used a number of criteria to identify priority basins, with certain thresholds (like the threshold of 'at least 1% of the total blue water footprint should be located in the basin') that can be considered as subjective choices. Obviously, changing thresholds will lead to longer or shorter lists of 'priority basins'.

Despite the limitations of the study, it has been proven that it is possible to make a rough sketch of where different economic sectors contribute to scarcity within the country and of which consumer goods contribute to water scarcity in specific river basins outside the country. The study shows that analysis of the external water footprint of a nation is necessary to get a picture of how national consumption depends on foreign water resources.

5 Water footprint scenarios for 2050: A global analysis and case study for Europe[4]

Abstract

This study develops water footprint scenarios for 2050 based on a number of drivers of change: population growth, economic growth, production/trade pattern, consumption pattern (dietary change, bioenergy use) and technological development. Our study comprises two assessments: one for the globe as a whole, distinguishing between 16 world regions, and another one for Europe, whereby we zoom in to the country level. The objective of the global study is to understand the changes in the water footprint of production and consumption for possible futures by region and to elaborate the main drivers of this change. In addition, we assess virtual water flows between the regions of the world to show dependencies of the regions on water resources in the other regions under different possible futures. In the European case study, our objective is to assess the water footprint of production and consumption at country level and Europe's dependence on water resources elsewhere in the world. We constructed four scenarios, which are structured along two axes, representing two key dimensions of uncertainty: globalisation versus regional self-sufficiency, and economy-driven development versus development driven by social and environmental objectives. The two axes create four quadrants, each of which represents a scenario: global markets (S1), regional markets (S2), global sustainability (S3) and regional sustainability (S4).

The WF of production in the world in 2050 has increased by 130% in S1 relative to the year 2000. In S2, the WF of production shows and increase of 175%, in S3 30% and in S4 46%. Among the scenarios, S1 and S2 have a higher WF of production as the world consumes more animal-based products. Scenario S2 yields the largest WF of production due to a larger population size and a higher demand in biofuels than S1. When the world food consumption depends less on animal products (S3 and S4), the increase in the WF of production becomes less. The WF of consumption in the world increases by +130% relative

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[4] Based on Ercin and Hoekstra (2012a)

to 2000 for the S1 scenario. It increases by +175% in S2, +30% in S3 and +46% in S4. The high increase in the WF of consumption for S1 and S2 can, for a significant part, be explained by increased meat consumption. When we compare trade liberalization (S1 and S3) to self-sufficiency scenarios (S3 and S4), it is observed that trade liberalization decreases the WF of consumption globally. The world average WF of consumption per capita increases by +73% in S1, +58% in S2, -2% in S3 and 10% in S4 compared to 2000 volumes.

The total WF of production in Western Europe increases by +12% in S1 and +42% in S2 relative to 2000 values. It decreases 36% in S3 and 29% in S4. Eastern Europe increases its WF of production by +150% and +107% in S1 and S2 compared to 2000, respectively. The increase is lower in S3 and S4 than in the other scenarios, but volumes are 36% and 31% higher than in 2000, respectively. The total WF of consumption in WEU increases by 28% and 52% in S1 and S2 compared to 2000. The WF of consumption in WEU decreases by -19% in S3 and -20% in S4. EEU increases its WF of consumption in all scenarios compared to 2000, by +143% in S1, +75% in S2, +17% in S3 and +20% in S4. The WF of consumption per capita in WEU increases by +30% in S1 and +22% in S2 and decreases by -18% in S3 and -28% in S4. EEU has a higher WF of consumption per capita in 2050 than 2000 with an increase of 186% in S1, 57% in S2, 38% in S3 and 23% in S4.

This study shows how different driver will change the level of water consumption and pollution globally in 2050. These estimates can form an important basis for a further assessment of how humanity can mitigate future freshwater scarcity. We showed with this study that reducing humanity's water footprint to sustainable levels is possible even with increasing populations, provided that consumption patterns change. This study can help to guide corrective policies at both national and international levels, and to set priorities for the years ahead in order to achieve sustainable and equitable use of the world's fresh water resources.

5.1 Introduction

Availability of freshwater in sufficient quantities and adequate quality is a prerequisite for human societies and natural ecosystems. In many parts of the world, excessive freshwater consumption and pollution by human activities put enormous pressure on this availability as well as on food security, environmental quality, economic development and social well-being. Competition over freshwater resources has been increasing during decades due to a growing population, economic growth, increased demand for agricultural products for both food and non-food use, and a shift in consumption patterns towards more meat and sugar based products (Shen et al., 2008; Falkenmark et al., 2009; De Fraiture and Wichelns, 2010; Strzepek and Boehlert, 2010). It looks like today's problems related to freshwater scarcity and pollution will be aggravated in the future due to a significant increase in demand for water and a decrease in availability and quality. Many authors have estimated that our dependency on water resources will increase significantly in the future and this brings problems for future food security and environmental sustainability (Rosegrant et al., 2002; Alcamo et al., 2003a; Bruinsma, 2003; 2009; Rosegrant et al., 2009). A recent report estimates that global water withdrawal will grow from 4,500 billion m^3/year today to 6,900 billion m^3/year by 2030 (McKinsey, 2009).

Scenario analysis is a tool to explore the long-term future of complex socio-ecological systems under uncertain conditions. This method can and indeed has been used to assess possible changes to global water supply and demand. Such studies have been an interest not only of scientists but also of governmental agencies, businesses, investors and the public at large. Many reports have been published to assess the future status of water resources since the 1970s (Falkenmark and Lindh, 1976; Kalinin and Bykov, 1969; Korzun et al., 1978; L'vovich, 1979; Madsen et al., 1973; Schneider, 1976). Water scenario studies address changes in future water availability and/or changes in future water demand. Some of the recent scenario studies focused on potential impacts of climate change and socio-economic changes on water availability (e.g. Arnell, 1996, 2004; Milly et al., 2005; Fung et al., 2011). Other scenario studies also included the changes in water demand (Alcamo et al., 1996; Seckler, 1998; Alcamo et al., 2000; Shiklomanov, 2000; Vörösmarty et al., 2000; Rosegrant et al. 2002, 2003; Alcamo et al., 2003a, b, 2007).

The major factors that will affect the future of global water resources are: population growth and concentration, economic growth, changes in production and trade patterns, increasing competition over water because of increased demands for domestic, industrial and agricultural purposes and the way in which different sectors of society will respond to increasing water scarcity and pollution. These factors are also mentioned in World Water Scenarios to 2050, a preparatory study on how to construct the upcoming generation of water scenarios by UNESCO and the United Nations World Water Assessment Programme (Cosgrove and Cosgrove, 2012; Gallopín, 2012). In this study, ten different drivers of change are identified as critical to assess water resources in the long-term future: demography, economy, technology, water stocks, water infrastructure, climate, social behaviour, policy, environment and governance.

In this study, we focus on water demand scenarios. In Table 5.1, we compare the scope of the current study with other recent water demand scenario studies. Vörösmarty et al. (2000) estimated agricultural, industrial and domestic water withdrawal for 2025, distinguishing single trajectories for population growth, economic development and change in water use-efficiency. The analysis was carried out at a 30′ grid resolution. Shiklomanov (2000) assessed water withdrawals and water consumption for 26 regions of the world for the year 2025. He projected agricultural, industrial and municipal water use considering population, economic growth and technology change (water efficiency). Another global water scenario study was undertaken by Rosegrant et al. (2002; 2003), who addressed global water and food security for the year 2025. They studied irrigation, livestock, domestic and industrial water withdrawal and consumption in 69 river basins under three main scenarios. Compared to other recent studies, their study includes the most extensive list of drivers of change: population growth, urbanization, economic growth, technology change, policies and water availability constraints. Technology change was addressed in terms of irrigation efficiency, domestic water use efficiency and growth in crop and animal yields. Policy drivers included water prices, water allocation priorities among sectors, commodity price policy as defined by taxes and subsidies on commodities. Climate change effects on water demand were not included in the study, but three alternative water availability constraints were included. Changes in food demand, production and trade were estimated for each scenario based on the drivers distinguished. The effect of increased biofuel consumption was not included. Different trajectories were considered for each driver, except for the economic and demographic drivers. Population growth, the speed of urbanization and economic growth were held constant across all scenarios. Alcamo et al. (2003a) analysed the change in water withdrawals for future business-as-usual conditions in 2025 under the assumption that current trends in population, economy and technology continue. They studied changes in water withdrawal at a 0.5° spatial resolution. A more recent assessment by Alcamo et al. (2007) improved their previous study by distinguishing two alternative trajectories for population and economic growth, based on the A2 and B2 scenarios of the IPCC for the years 2025, 2055 and 2075. Shen et al. (2008) studied changes in water withdrawals in the agricultural, industrial and domestic sectors for the years 2020, 2050 and 2070. They addressed socio-economic changes (population, GDP, water use efficiency) as described in four IPCC scenarios (A1, A2, B1 and B2), disaggregating the world into 9 regions. One of the most extensive water demand scenario studies was done by De Fraiture et al. (2007) and De Fraiture and Wichelns (2010). These studies focused on alternative strategies for meeting increased demands for water and food in 2050. They elaborated possible alternatives under four scenarios for 115 socio-economic units (countries and country groups). Their analysis distinguished water demand by green and blue water consumption. The agriculture sector was analysed considering 6 crop categories and livestock separately. The industrial sector was schematized into the manufacturing industry and the thermo-cooling sector. Many drivers were addressed explicitly, like food demand, trade structure, water productivity, change in water policies and investments, in addition to the conventional drivers of population and economic growth. Despite covering most of the critical drivers, they excluded effects of climate change and biofuel demand from their study. Most of these studies have paid little attention to the fact that, in the end, total water consumption and pollution relate to the amount and type of commodities we consume and to the structure of the global economy and trade, that supplies the various consumer goods and services to us. None of the global scenario studies addressed the question of how alternative consumer choices influence the future status of the water resources except Rosegrant et al. (2002; 2003). In addition, the links between trends in consumption, trade, social and economic development have not yet been fully integrated.

Table 5.1. Comparison of existing global water demand scenarios with the current study.

Study	Study characteristics	Sectoral disaggregation	Drivers used to estimate future water demand (no. of trajectories distinguished)
Vörösmarty et al. (2000)	Time horizon: 2025 Spatial scale: 30′ grid resolution Scenarios: 1 Scope: Blue water withdrawal	Agriculture Industry Domestic	Population growth (1) Economic growth (1) Technology change (1)
Shiklomanov (2000)	Time horizon: 2025 Spatial scale: 26 regions Scenarios: 1 Scope: Blue water withdrawal and consumption	Agriculture Industry Domestic	Population growth (1) Economic growth (1) Technology change (1)
Rosegrant et al. (2002; 2003)	Time horizon: 2025 Spatial scale: 69 river basins Scenarios: 3 Scope: Blue water withdrawal and consumption	Agriculture: 16 sub-sectors Industry Domestic	Population growth (1) Urbanization (1) Economic growth (1) Technology change (3) Policies (3) Water availability constraints (3)
Alcamo et al. (2003a)	Time horizon: 2025 Spatial scale: 0.5° spatial resolution Scenarios: 1 Scope: Blue water withdrawal	Agriculture Industry Domestic	Population growth (1) Economic growth (1) Technology change (1)
Alcamo et al. (2007)	Time horizon: 2025/2055/2075 Spatial scale: 0.5° spatial resolution Scenarios: 2 Scope: Blue water withdrawal	Agriculture Industry Domestic	Population growth (2) Economic growth (2) Technology change (1)
Shen et al. (2008)	Time horizon: 2020/2050/2070 Spatial scale: 9 regions Scenarios: 4 Scope: Blue water withdrawal	Agriculture Industry Domestic	Population growth (4) Economic growth (4) Technology change (4)
De Fraiture and Wichelns (2010)	Time horizon: 2050 Spatial scale: 115 socio-economic units Scenarios: 4 Scope: Green and blue water consumption	Agriculture: 7 sub-sectors Industry: 2 sub-sectors Domestic	Population growth (1) Economic growth (1) Production and trade patterns change (4) Technology change (4) Consumption patterns - diet (1)
Current study	Time horizon: 2050 Spatial scale: 227 countries, 16 regions Scenarios: 4 Scope: Green and blue water consumption, pollution as grey water footprint	Agriculture: 20 sub-sectors Industry Domestic	Population growth (3) Economic growth (4) Production and trade patterns change (4) Technology change (2) Consumption patterns - diets (2) Consumption patterns – biofuel (3)

The current study develops water footprint scenarios for 2050 based on a number of drivers of change: population growth, economic growth, production/trade pattern, consumption pattern (dietary change, bioenergy use) and technological development. It goes beyond the previous global water demand scenario studies by a combination of factors: (i) it addresses blue and green water consumption instead of blue water withdrawal volumes; (ii) it considers water pollution in terms of the grey water footprint; (iii) it analyses agricultural, domestic as well as industrial water consumption; (iv) it disaggregates consumption along major commodity groups; (v) it integrates all major critical drivers of change under a single, consistent framework. In particular, integrating all critical drivers is crucial to define policies for wise water governance and to help policy makers to understand the long-term consequences of their decisions across political and administrative boundaries.

We have chosen in this study to look at water footprint scenarios, not at water withdrawal scenarios as done in most of the previous studies. We explicitly distinguish between the green, blue and grey water footprint. The green water footprint refers to the consumptive use of rainwater stored in the soil. The blue water footprint refers to the consumptive use of ground or surface water. The grey water footprint refers to the amount of water contamination and is measured as the volume of water required to assimilate pollutants from human activities (Hoekstra et al., 2011).

Our study comprises two assessments: one for the globe as a whole, distinguishing between 16 world regions, and another one for Europe, whereby we zoom in to the country level. The objective of the global study is to understand the changes in the water footprint of production and consumption for possible futures by region and to elaborate the main drivers of this change. In addition, we assess virtual water flows between the regions of the world to show dependencies of the regions on water resources in the other regions under different possible futures. In the European case study, our objective is to assess the water footprint of production and consumption at country level and Europe’s dependence on water resources elsewhere in the world.

5.2 Method

5.2.1 Scenario description

For constructing water footprint scenarios, we make use of global scenario exercises of the recent past as much as possible. This brings two main advantages: building our scenarios on well-documented possible futures and providing readers quick orientation of the storylines. As a starting point, we used the 2×2 matrix system of scenarios developed by the IPCC (Nakicenovic et al., 2000). These scenarios are structured along two axes, representing two key dimensions of uncertainty: globalisation versus regional self-sufficiency, and economy-driven development versus development driven by social and environmental objectives. The two axes create four quadrants, each of which represents a scenario: global markets (S1), regional markets (S2), global sustainability (S3) and regional sustainability (S4) (Figure 5.1). Our storylines resemble the IPCC scenarios regarding population growth, economic growth, technological development and governance. For the purpose of our analysis, we had to develop most of the detailed assumptions of the scenarios ourselves, but the assumptions were inspired from the storylines of the existing IPCC scenarios. The scenarios are consistent and tell reliable stories about what may happen in future. It is important to understand that our scenarios are not predictions of the future; they rather show alternative perspectives on how water footprints may develop towards 2050.

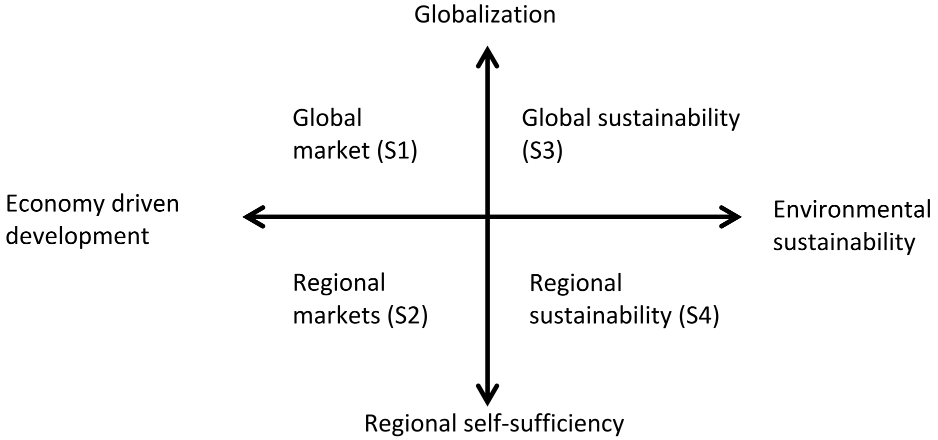

Figure 5.1. The four scenarios distinguished in this study.

First, we constructed a baseline for 2050, which assumes a continuation of the current situation into the future. The four scenarios were constructed based on the baseline by using different alternatives for the drivers of change. The baseline constructed for 2050 assumes the per capita food consumption and non-food crop demand as in the year 2000. It also considers technology, production and trade as in the year 2000. Economic growth is projected as described in IPCC scenario B2. Climate change is not taken into account. The increase in population size is taken from the medium-fertility population projection of the United Nations (UN, 2011). Therefore, changes in food and non-food consumption and in the water footprint of agriculture and domestic water supply are only subject to population growth. The industrial water footprint in the baseline depends on economic growth.

Scenario S1, *global market*, is inspired by IPCC's A1 storyline. The scenario is characterized by high economic growth and liberalized international trade. The global economy is driven by individual consumption and material well-being. Environmental policies around the world heavily rely on economic instruments and long-term sustainability is not in the policy agenda. Trade barriers are gradually removed. Meat and dairy products are important elements of the diet of people. A rapid development of new and efficient technologies is expected. Energy is mainly sourced from fossil fuels. Low fertility and mortality are expected.

Scenario S2, *regional markets,* follows IPCC's A2 storyline. It is also driven by economic growth, but the focus is more on regional and national boundaries. Regional self-sufficiency increases. Similar to S1, environmental issues are not important factors in decision-making, new and efficient technologies are rapidly developed and adopted, and meat and dairy are important components in the diets of people. Fossil fuels are dominant, but a slight increase in the use of biofuels is expected. Population growth is highest in this scenario.

Scenario S3, *global sustainability*, resembles IPCC's B1 storyline. The scenario is characterized by increased social and environmental values, which are integrated in global trade rules. Economic growth is slower than in S1 and S2 and social equity is taken into consideration. Resource efficient and clean technologies are developed. As the focus is on environmental issues, meat and dairy product consumption is decreased. Trade becomes more global and liberalized. Reduced agro-chemical use and cleaner industrial activity is expected. Population growth is the same as for S1.

Scenario S4, *local sustainability*, is built on IPCC's B2 storyline and dominated by strong national or regional values. Self-sufficiency, equity and environmental sustainability are at the top of the policy agenda. Slow long-term economic growth is expected. Personal consumption choices are determined by social and environmental values. As a result, meat consumption is significantly reduced. Pollution in the agricultural and industrial sectors is lowered. Biofuel use as an energy source is drastically expanded.

These scenarios are developed for 16 different regions of the world for the year 2050. We used the country classification and grouping as defined in Calzadilla (2011a). The regions covered in this study are: the USA; Canada; Japan and South Korea (JPK); Western Europe (WEU); Australia and New Zealand (ANZ); Eastern Europe (EEU); Former Soviet Union (FSU); Middle East (MDE); Central America (CAM); South America (SAM); South Asia (SAS); South-east Asia (SEA); China (CHI); North Africa (NAF); Sub-Saharan Africa (SSA) and the rest of the world (RoW). The composition of the regions is given in Appendix 5.1.

5.2.2 Drivers of change

We identified five main drivers of change: population growth, economic growth, consumption patterns, global production and trade pattern and technology development. Table 5.2 shows the drivers and associated assumptions used in this study.

Population growth

Changes in population size are a key factor determining the future demand for goods and services, particularly for food items (Schmidhuber and Tubiello, 2007; Godfray et al., 2010; Kearney, 2010; Lutz and KC, 2010). The IPCC scenarios (A1, A2, B1, and B2) used population projections from both the United Nations (UN) and the International Institute for Applied Systems Analysis (IIASA). The lowest population trajectory is assumed for the A1 and B1 scenario families and is based on the low population projection of IIASA. The population in the A2 scenario is based on the high population projection of IIASA. IPCC uses UN's medium-fertility scenario for B2. We used UN-population scenarios (UN, 2011) for all our scenarios: the UN high-fertility population scenario for S2, the UN medium-fertility population scenario for S4 and the UN low-fertility population scenario for S1and S3. Population forecasts per region are given in Appendix 5.2.

Table 5.2. Drivers and assumptions per scenario.

Driver		Scenario S1: Global market	Scenario S2: Regional markets	Scenario S3: Global sustainability	Scenario S4: Regional sustainability
Population growth		Low-fertility	High-fertility	Low-fertility	Medium fertility
Economic growth*		A1	A2	B1	B2
Consumption patterns	Diet	Western high meat	Western high meat	Less meat	Less meat
	Bio-energy demand	Fossil-fuel domination	Biofuel expansion	Drastic biofuel expansion	Drastic biofuel expansion
Global production and trade pattern		Trade liberalization (A1B+ TL2)	Self-sufficiency (A2+SS1)	Trade liberalization (A1B+TL1)	Self-sufficiency (A2+SS2)
Technology development		Decrease in blue water footprints in agriculture	Decrease in blue water footprints in agriculture	Decrease in green and grey water footprints in agriculture Decrease in blue and grey water footprints in industries and domestic water supply	Decrease in green and grey water footprints in agriculture Decrease in blue and grey water footprints in industries and domestic water supply

*The scenario codes refer to the scenarios as used by the IPCC (Nakicenovic et al., 2000)

Economic growth

We assumed that the water footprint of industrial consumption is directly proportional to the GDP. We used GDP changes as described in IPCC scenarios A1, A2, B1, and B2 for S1, S2, S3 and S4, respectively. The changes in GDP per nation are taken from the database of the Center for International Earth Science Information Network of Columbia University (CIESIN, 2002).

Consumption patterns

We distinguished two alternative food consumption patterns based on Erb et al. (2009b):

- ‘Western high meat’: economic growth and consumption patterns accelerate in the coming decades, leading to a spreading of western diet patterns. This scenario brings all regions to the industrialised diet pattern.
- ‘Less meat’: each regional diet will develop towards the diet of the country in the region that has the highest calorie intake in 2000, but only 30% of the protein comes from animal sources.

We used the ‘western high meat’ alternative for S1 and S2 and the ‘less meat’ for S3 and S4. Erb et al. (2009b) provide food demand per region in terms of kilocalories per capita for 10 different food categories: cereals; roots and tubers; pulses; fruits and vegetables; sugar crops; oil crops; meat; pigs, poultry and eggs; milk, butter and other dairy products; and other crops. We converted kilocalorie intake per capita to kg/cap by using conversion factors taken from FAO for the year 2000 (FAO, 2012). We also took seed and waste ratios per food category into account while calculating the total food demand in 2050.

Per capita consumption patterns for fibre crops and non-food crop products were kept constant as it was in 2000. It is assumed that the change in demand for these items is only driven by population size. Per capita consumption values are taken from FAOSTAT for the year 2000 (FAO, 2012).

We integrated three different biofuel consumption alternatives into our scenarios. We used biofuel consumption projections as described by Msangi et al. (2010). They used the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) to estimate biofuel demand for 2050 for three different alternatives:

- Baseline: Biofuel demand remains constant at 2010 levels for most of the countries. This scenario is a conservative plan for biofuel development. This is used in S1.
- Biofuel expansion: In this scenario, it is assumed that there will be an expansion in biofuel demand towards 2050. It is based on current national biofuel plans. This is applied in S2.
- Drastic biofuel expansion: Rapid growth of biofuel demand is foreseen for this scenario. The authors developed this scenario in order to show the consequences of going aggressively for biofuels. This option is used for the S3 and S4 scenarios.

Msangi et al. (2010) provide biofuel demand in 2050 in terms of crop demands for the USA, Brazil and the EU (Table 5.3). We translated their scenarios to the regions as defined in our study by using the biofuel demand shares of nations for the year 2000. The demand shares are taken from the US Energy Information Administration (EIA, 2012).

Table 5.3. Biofuel demand in 2050 for different scenarios (in tons.)

Crop	**Region**	**Baseline**	**Biofuel expansion**	**Drastic biofuel**
Cassava	World	660,000	10,640,000	21,281,000
Maize	EU	97,000	1,653,000	3,306,000
	USA	35,000,000	130,000,000	260,000,000
	RoW	2,021,000	30,137,000	60,274,000
Oil seeds	Brazil	16,000	197,000	394,000
	EU	1,563,000	18,561,000	37,122,000
	USA	354,000	3,723,000	7,447,000
	RoW	530,000	5,172,000	10,344,000
Sugar	Brazil	834,000	14,148,000	28,297,000
	USA	265,000	5,840,000	11,680,000
	RoW	163,000	2,785,000	5,571,000
Wheat	EU	1,242,000	15,034,000	30,067,000
	RoW	205,000	3,593,000	7,185,000

Source: Msangi et al. (2010).

Global production and trade pattern

The regional distribution of crop production is estimated based on Calzadilla et al. (2011a), who estimated agricultural production changes in world regions by taking climate change and trade liberalization into account (Appendix 5.4). They used a global computable general equilibrium model called GTAP-W for their estimations. The detailed description of the GTAP-W and underpinning data can be found in Berrittella et al. (2007) and Calzadilla et al. (2010; 2011b). In their study, trade liberalization is implemented by considering two different options:

- Trade liberalization 1 (TL1): This scenario assumes a 25% tariff reduction for all agricultural sectors. In addition, they assumed zero export subsidies and a 50% reduction in domestic farm support.
- Trade liberalization 2 (TL2): It is a variation of the TL1 case with 50% tariff reduction for all agricultural sectors.

In addition, Calzadilla et al. (2011a) elaborated potential impacts of climate change on production and trade patterns considering IPCC A1B and A2 emission scenarios. In total, they constructed 8 scenarios for 2050 considering two climate scenarios (A1B and A2), two trade liberalization scenarios (TL1 and TL2) and their combinations (A1B+TL1, A1B+TL2, A2+TL1, A2+TL2). For the S1 and S3 scenarios, we considered production changes as estimated in A1B+TL2 and A1B+TL1 respectively. We used the A2 for the S2 and S4 scenarios but we also introduced self-sufficiency options to S2 and S4 as described below:

- Self-sufficiency (SS1): This alternative assumes 20% of reduction in import of agricultural products (in tons) by importing regions compared to the baseline in 2050. Therefore, exporting regions are reducing their exports by 20%. This is applied in S2.
- Self-sufficiency (SS2): In this alternative, we assumed 30% reduction in imports by importing nations relative to the baseline in 2050. This option is used for S4.

Technology development

The effect of technology development is considered in terms of changes in water productivity in agriculture, wastewater treatment levels and water use efficiencies in industry. For scenarios S3 and S4, we assumed that the green water footprints of crops get reduced due to yield improvements and for scenarios S1 and S2 we assumed that the blue water footprints of crops diminish as a result of improvements in irrigation technology. We assigned a percentage decrease to green and blue water footprints for each scenario based on the scope for improvements in productivity as given in De Fraiture et al. (2007), who give levels of potential improvement per region in a qualitative sense. For scenarios S1 and S2 we assume reductions in blue water footprints in line with the scope of improved productivity in irrigated agriculture per region as given by De Fraiture et al. (2007). For scenarios S3 and S4 we assume reductions in green water footprints in line with the scope for improved productivity in rainfed agriculture per region, again taking the assessment by De Fraiture et al. (2007) as a guideline. For scenarios S3 and S4 we took reductions in grey water footprints similar to the reductions in green water footprints. To quantify the qualitative indications of reduction potentials in De Fraiture et al. (2007), we assigned a reduction percentage of 20% to 'some' productivity improvement potential, 30% to 'good' productivity improvement potential and 40% for 'high' productivity improvement potential.

To reflect improvements in wastewater treatment levels and blue water use efficiencies, we applied a 20% reduction in the blue and grey water footprints of industrial products and domestic water supply in S3 and S4.

5.2.3 Estimation of water footprints

This study follows the terminology of water footprint assessment as described in the Water Footprint Assessment Manual (Hoekstra et al., 2011). The water footprint is an indicator of water use that looks at both direct and indirect water use of a consumer or producer. Water use is measured in terms of water volumes consumed (evaporated or incorporated into the product) and polluted per unit of time. The water footprint of an individual or community is defined as the total volume of freshwater that is used to produce the goods and services consumed by the individual or community. The 'water footprint of national (regional) production' refers to the total freshwater volume consumed or polluted within the territory of the nation (region). This includes water use for making products consumed domestically but also water use for making export products. It is different from the 'water footprint of national (regional) consumption', which refers to the total amount of water that is used to produce the goods and services consumed by the inhabitants of the nation (region). This refers to both water use within the nation (region) and water use outside the territory of the nation (region), but is restricted to the water use behind the products consumed within the nation (region). The water footprint of national (regional) consumption thus includes an internal and external component. The internal water footprint of consumption is defined as the use of domestic water resources to produce goods and services consumed by the national (regional) population. It is the sum of the water footprint of the production minus the volume of virtual-water export to other nations (regions) insofar as related to the export of products produced with domestic water resources. The external water footprint of consumption is defined as the volume of water resources used in other nations (regions) to produce goods and services consumed by the population in the nation (region) considered. It is equal to the virtual-water import minus the volume of virtual-water export to other nations (regions) because of re-export of imported products.

5.2.3.1 Water footprint of agricultural consumption and production

Regional consumption of food items

The food consumption $c_f(c,r)$ in ton/year related to commodity group c in region r in the year 2050 is defined as:

$$c_f(c,r) = pop(r) \times kcal(c,r) \times f_{ton/kcal} \tag{5.1}$$

where $pop(r)$ is the population in region r in 2050 and $kcal(c,r)$ the daily kilocalorie intake per capita related to commodity group c in region r in this year. The coefficient $f_{ton/kcal}$ is the conversion factor from kcal/cap/day to ton/cap/year, which is obtained from FAO (2012). Population and kcal values per region for the year 2050 are obtained from UN (2011) and Erb et al. (2009b), respectively.

Regional consumption of fibres and other non-food items

The fibre and other non-food consumption $c_{nf}(c,r)$, ton/year, related to commodity group *c* in region *r* in 2050 is defined as:

$$c_{nf}(c,r) = \sum_n (pop(n) \times f_c(c,n)|_{t=2000}) \tag{5.2}$$

where $f_c(c,n)|_{t=2000}$ is the per capita demand for commodity group *c* in nation *n* that is located in region *r,* in 2000, which is obtained from FAO (2012).

Regional consumption of biofuel

Crop use for biofuels $c_b(c,r)$, *in* ton/year, related to commodity group *c* in region *r* in 2050 is defined as:

$$c_b(c,r) = \sum_n (C_b(c) \times f_b(n)|_{t=2000}) \tag{5.3}$$

where $C_b(c)$ is the crop use for biofuels in 2050 regarding commodity group *c,* taken according to one of the scenarios as defined in Msangi et al. (2010), and $\mathrm{f_b(n)|_{t=2000}}$ the energy crop share in 2000 of nation *n* that is located in region *r* is taken from EIA (2012).

Global consumption

Total consumption for each commodity group in the world, in ton/year, is calculated as:

$$C_f(c) = \sum_r c_f(c,r) \tag{5.4}$$

$$C_{nf}(c) = \sum_r c_{nf}(c,r) \tag{5.5}$$

$$C_b(c) = \sum_r c_b(c,r) \tag{5.6}$$

Total production

We assume that, per commodity group, total production meets total consumption:

$$P_f(c) = C_f(c) \tag{5.7}$$

$$P_{nf}(c) = C_{nf}(c) \tag{5.8}$$

$$P_b(c) = C_b(c) \tag{5.9}$$

Production shares of the regions

The expected production $p(c,r)$ (ton/year) related to commodity group *c* in region *r* is defined as the multiplication of the production share $f_p(c,r)$ of region *r* and the total production of commodity group *c* in the world.

$$p(c,r) = P(c) \times f_p(c,r) \tag{5.10}$$

Production shares of the regions per scenario are taken from Calzadilla et al. (2011a).

Trade

The surplus $s(c,r)$ (ton/year) related to commodity group *c* in region *r* is defined as the difference between in production *p* and consumption *c*:

$$s(c,r) = p(c,r) - c(c,r) \tag{5.11}$$

Net import i (ton/year) per commodity group and per region is equal to the absolute value of the surplus if *s* is negative. Similarly, net export *e* is equal to the surplus if *s* is positive:

$$i\,(c,r) = \begin{cases} |s|, & s < 0 \\ 0, & s \geq 0 \end{cases} \tag{5.12}$$

$$e\,(c,r) = \begin{cases} 0, & s \leq 0 \\ s, & s > 0 \end{cases} \tag{5.13}$$

Trade, *T* (tons/year) of commodity group *c*, from exporting region r_e to importing region r_i is estimated as:

$$T\left(c, r_{e,} r_i\right) = i\left(c, r_i\right) \times f_e\left(c, r_e\right) \tag{5.14}$$

where $i(c, r_i)$ refers to the amount of import of commodity group c by importing region r_i and f_e to the export fraction of exporting region r_e, which is calculated as the share of export of region r_e in the global export of commodity group c.

Unit water footprint per agricultural commodity groups per region

The unit water footprint, $WF(c, r)$ (m^3/ton), of commodity group c produced in region r is calculated by multiplying the unit WF of the commodity group in 2000 with a factor, α, to account for productivity increase:

$$WF(c, r) = WF\ (c, r)|_{t=2000} \times \propto (r) \tag{5.15}$$

The factor α is determined per scenario as described in Section 5.2.2. The values taken for α are presented in Appendix 5.3. The unit water footprints of commodities per region in 2000 are obtained from Mekonnen and Hoekstra (2010a; b).

Water footprint of agricultural production

The water footprint of production related to commodity group c in region r is calculated as:

$$WF_{p,a}\ (c, r) = p\ (c, r) \times WF\ (c, r) \tag{5.16}$$

Virtual water flows

The net virtual water flow VW (m^3/year) from exporting region r_e to importing region r_i as a result of trade in commodity group c is calculated by multiplying the commodity trade $T\left(c, r_{e,} r_i\right)$ between the regions and the unit water footprint $WF(c, r)$of the commodity group in the exporting region:

$$VW\left(c, r_{e,} r_i\right) = T\left(c, r_{e,} r_i\right) \times WF\left(c, r_{e,}\right) \tag{5.17}$$

Water footprint of consumption of agricultural commodities

The water footprint of consumption ($WF_{c,a}(c,r)$, Mm^3/year) related to the consumption of commodity group c in region r is calculated as the water footprint of production of that commodity, $WF_p(c,r)$, in region r plus the net virtual-water import to the region related to that commodity.

$$WF_{c,a}(c,r) = WF_p(c,r) + \sum_{r_e} VW\left(c, r_{e,} r_i\right) \tag{5.18}$$

5.2.3.2 Water footprint of industrial consumption and production

Water footprint of consumption of industrial commodities

The water footprint related to the consumption of industrial commodities ($WF_{c,i}\,(r)$, Mm^3/year) in region r in 2050 is calculated by multiplying the water footprint of industrial consumption in 2000 by the growth in GDP and a factor β representing productivity increase (see Section 5.2.2).

$$WF_{c,i}\,(r) = \sum_n (WF_{c,i}\,(n)\big|_{t=2000} \times \frac{GDP_{2050}(n)}{GDP_{2000}(n)} \times \beta) \tag{5.19}$$

The water footprint related to consumption of industrial commodities in nation n in 2000 is taken from Mekonnen and Hoekstra (2011b). GDP changes are taken from CIESIN (2002).

Water footprint of industrial production

The water footprint of industrial production ($WF_{p,i}\,(r)$, Mm^3/year) in region r in 2050 is calculated by multiplying the global water footprint of industrial consumption in 2050 by the share of the water footprint of industrial production of region r in the global water footprint of industrial production in 2000.

$$WF_{p,i}\,(r) = \sum_r WF_{c,i}\,(r) \times \frac{WF_{p,i}\,(r)}{\sum_r WF_{p,i}\,(r)}\bigg|_{t=2000} \tag{5.20}$$

The water footprint of industrial production per region r in 2000 is taken from Mekonnen and Hoekstra (2011b).

5.2.3.3 Water footprint of domestic water supply

The water footprint of domestic water supply per region in 2050, $WF_{dom}(r)$(Mm^3/year), is calculated by multiplying the population in 2050 with the water footprint of domestic water supply per capita in 2000 and factor β representing productivity increase:

$$WF_{dom}(r) = \sum_n (pop(n) \times WF_{dom,cap}(n)\big|_{t=2000} \times \beta) \qquad (5.21)$$

The data for the water footprint of domestic water supply in 2000 are taken from Mekonnen and Hoekstra (2011b).

5.2.4 European case study

In the global study, Europe is described by two regions: Western and Eastern Europe. To enable us to make a more detailed analysis for Europe, we use country specific data on population change and per capita food consumption for Western and Eastern Europe. We down-scaled the results obtained for Western and Eastern Europe to the nations within Europe. To estimate production, trade, virtual water flows, and water footprint of production and consumption per country within Europe, we followed the same methodology as described in the 5.2.3. The regions in the equations are replaced by the nations of Europe. The production distribution among the European countries in 2050 is done by taking the production patterns in 2000 (FAO, 2012).

5.3 Global water footprint in 2050

5.3.1 Water footprint of production

The WF of production in the world in 2050 has increased by 130% in S1 relative to the year 2000 (Table 5.4). In S2, the WF of production shows and increase of 175%, in S3 30% and in S4 46%. The increase in the total WF of production is highest for industrial products in S1 (600%). This increase is less for the other scenarios as they have a lower increase in GDP than S1. The WF of agricultural production is higher in S1 and S2 (112 and 180%

more than 2000 values) than in S3 and S4 (18 and 38% more than 2000), which is due to dietary differences between S1/S2 and S3/S4. Among the scenarios, S2 has the largest WF of production as it has the highest population and high meet consumption. The WF of production related to domestic water supply increases by 18% in S1, 55% in S2, -6% in S3 and 9% in S4.

In 2000, approximately 91% of the total WF of production is related to agricultural production, 5% to industrial production and 4% to domestic water supply. The WF of industrial production increases its share in the total for the S1, S2 and S4 scenarios.

In all scenarios, the WF of production is dominated by the green component. However, the share of the green component decreases from 76% in 2000 to 74% in 2050 in S1 (Figure 5.2). The share of the blue component decreases from 10% in 2000 to 7% in 2050 in S1. The grey WF increases its share from 14% in 2000 to 19% in S1. The shares of the green, blue and grey WF of production in S2 are 82, 7, and 11% respectively. The share of the green component falls down to 68 and 69% in S3 and S4, while an increase is observed in the share of blue WF.

Among the scenarios, S1 and S2 have a higher WF of production as the world consumes more animal-based products. Scenario S2 yields the largest WF of production due to a larger population size and a higher demand in biofuels than S1. When the world food consumption depends less on animal products (S3 and S4), the increase in the WF of production becomes less.

Among the regions, SAM and ANZ show the highest increase in the total WF of production in S1. The increase in ANZ is 217% for S1, 251% for S2, 54% for S3 and 33% for S4. The increase is quite significant for SAM as well (361, 422, 168, and 144% for S1, S2, S3 and S4, respectively). SSA increases its water footprint of production 181% in S1, 364% in S2, 81% in S3 and 184% in S4. The USA, CAM, Canada, SEA, EEU, FSU, MDE, NAF and SAS are the other regions, which have a higher WF of production in 2050 compared to 2000 in all scenarios.

The WF of JPK's production decreases for all scenarios. The change is -46% for S1, -21% for S2, -68% for S3 and -55% for S4. This relates to the fact that JPK increasingly externalizes its WF of consumption towards 2050. The WF of production in WEU increases in S1 and S2 by 12 and 42%, respectively, but decreases for S3 and S4, by 36 and 29% relative to 2000 values. The main reason for the decrease in S3 and S4 is due to dietary preferences, shifting from high to low meat content. Despite the increase in the WF of production in China in S1 and S2 (by 137 and 129%), a decrease is observed in S3 (6%).

Table 5.4. Percentage change in the water footprint of production compared to 2000. 'A' refers to WF of agricultural production, 'D' refers to WF of domestic water supply, 'I' refers to WF of industrial production and 'T' refers to total WF.

Region	S1				S2				S3				S4			
	A	D	I	T	A	D	I	T	A	D	I	T	A	D	I	T
USA	105	24	16	87	154	57	20	128	49	-1	-9	38	59	12	-13	46
Canada	139	26	57	118	193	58	44	161	84	1	37	70	80	13	18	66
WEU	19	-3	-45	12	51	22	-28	42	-34	-23	-57	-36	-28	-13	-46	-29
JPK	-52	-20	-16	-46	-24	1	-15	-21	-75	-36	-31	-68	-60	-28	-34	-55
ANZ	221	40	-75	217	255	77	-50	251	55	12	-77	54	34	26	-57	33
EEU	50	-24	833	150	85	0	274	107	-17	-39	393	36	-17	-30	355	31
FSU	46	-18	1,649	135	83	10	531	105	-12	-34	735	30	-11	-24	529	19
MDE	40	44	208	46	157	88	80	151	1	15	122	5	78	32	41	74
CAM	143	21	341	142	204	63	127	196	37	-3	198	39	44	13	142	45
SAM	372	24	474	361	441	66	158	422	172	-1	262	168	149	15	160	144
SAS	67	38	1,160	84	149	85	353	150	-10	11	1,495	16	25	28	653	36
SEA	127	32	953	151	191	76	257	188	32	6	458	45	37	22	400	49
CHI	89	-12	1,885	137	127	16	338	129	-22	-29	555	-6	-22	-19	967	6
NAF	32	43	533	44	81	90	236	85	2	14	651	17	27	32	112	29
SSA	179	122	863	181	367	183	243	364	78	78	649	81	184	101	335	184
RoW	114	-9	71	106	195	11	12	177	12	-27	-11	9	34	-20	110	36
World	112	18	601	130	180	55	158	175	18	-6	311	30	38	9	261	46

The WF of industrial production shows a drastic increase relative to 2000 for CHI, FSU and SAS in S1. Industrial WFs in these regions increase by a factor of more than 10 times, up to 18 times for CHI. Other regions with high industrial WF increase in S1 are

SSA, NAF, SEA, SAM and CAM. These regions also have a larger WF of industrial production in S2 as well. WEU, ANZ and JPK have a lower WF of industrial production in 2050 compared to 2000, in all scenarios.

The effect of trade liberalization versus increased self-sufficiency on the WF of production can be seen by observing the differences between S1 and S2 and between S3 and S4. Importing regions like MDE and SSA have a higher WF of production in S2 (regional markets) compared to S1 (global market) and a higher WF in S4 (regional sustainability) compared to S3 (global sustainability).

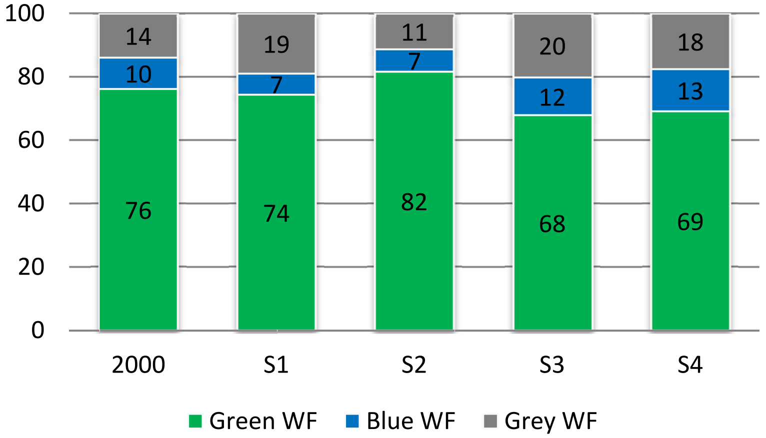

Figure 5.2. Green, blue and grey WF of production as a percentage of total WF in 2000 and 2050 according to the four scenarios.

We separately analysed the effect of trade liberalization and climate change on the WF of production in the world. For this purpose, we first run a scenario with a changed global production pattern under trade liberalization (TL1) as the only driver of change to the baseline in 2050. Next, we run a scenario with a changed global production pattern under climate change (A1B) as the only driver of change to the baseline in 2050. The results show that trade liberalization has a limited effect on the global WF of production (Figure 5.3). On regional basis, it increases the WF of production in Canada, CHI, JPK, ANZ, MDE, SAM and SEA and decreases in the regions the USA, WEU, EEU, FSU, CAM, NAF, SSA and SAS. However, in all cases the change is not more than 2%.

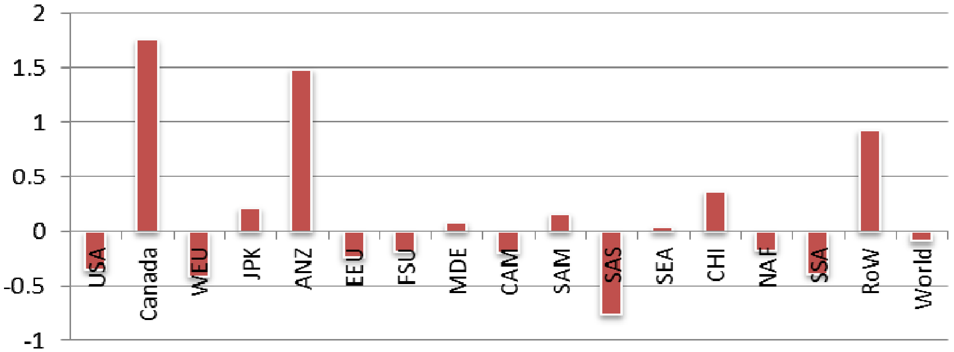

Figure 5.3. Percentage change of the WF of production by trade liberalization compared (TL1) to the baseline in 2050.

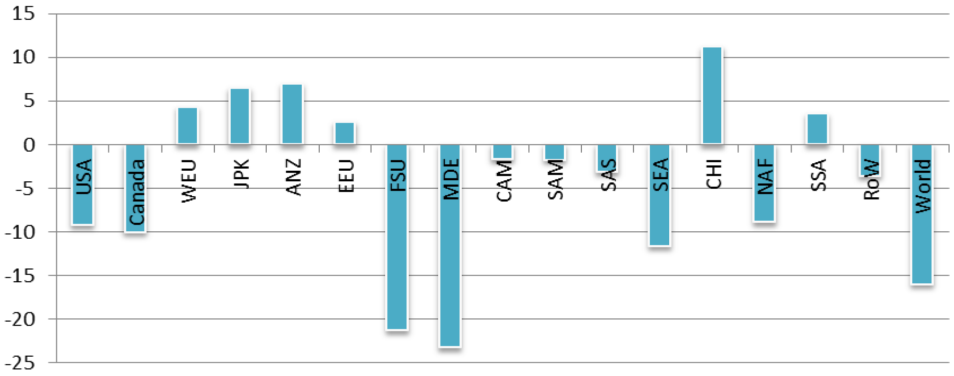

Figure 5.4. Percentage change of the WF of production by climate change (A1B) compared to the baseline in 2050.

On the contrary, the effect of climate change on the total WF of production is significant and results in a decrease of around 15% for the world (Figure 5.4). The effect of climate change is most visible in the USA, Canada, MDE, FSU, NAF and SEA, where a clear decrease is seen. Climate change affects the WF of production in the opposite direction in other regions, including CHI, ANZ, JPK, WEU, SSA and EEU.

5.3.2 Virtual water flows between regions

Net virtual water import per region for each scenario is given in Table 5.5. The regions WEU, JPK, SAS, MDE, NAF and SSA are net virtual water importers for all scenarios in 2050. The USA, Canada, ANZ, EEU, FSU, CAM, SAM, SEA and CHI are net virtual water exporters in 2050.

All net virtual water-exporting regions in 2000 stay net virtual water exporters in all 2050 scenarios. Net virtual water export from these regions increases in S1 and S2 compared to 2000, except Canada and SEA. SAM, FSU and the USA substantially increase their net virtual water export in S1 and S2. SAM becomes the biggest virtual water exporter in the world in 2050 for all scenarios and increases its net virtual water export around 10 times in S1 and S2. The change is also high in S3 and S4 with an increase by a factor 6 and 5, respectively. Another region that will experience a significant increase in net virtual water export is the FSU. Compared to 2000, the net virtual water flow leaving this region becomes 9 times higher in S1, 6 times in S2 and S3, and 4 times in S4. The net virtual water export from the USA increases by a factor 3 in both S1 and S2 relative to 2000. The net virtual export from the USA decreases in S3 and S4 compared to 2000. Although Canada continues to be a net virtual water exporter in 2050, its virtual water export decreases below the levels of 2000 for S1, S3 and S4. Despite still being a net virtual water exporter in 2050, SEA experience a decrease in the net virtual water export volumes compared to 2000 in all scenarios.

All net virtual water-importing regions in 2000 stay net virtual water importers in 2050 for all scenarios except CAM and CHI, which become net virtual water exporters in 2050. The net virtual water import by WEU stays below the 2000 volume for S2 and S4. Although JPK has a slightly higher net virtual water import in S1 and S2 than 2000, it decreases its net virtual water import for the other scenarios. SSA is the region where the highest increase in virtual water import is observed in 2050. Its net virtual water import rises drastically in S1 and S2 compared to 2000. Other regions with a significant increase in net virtual water import are MDE and SAS. The net virtual water import is the highest in S1 for all importing regions except SAS and NAF. WEU shows a different pattern, where the net virtual water import is the highest in S3. The reason behind this is the significant increase in biofuel demand in WEU in S3.

The regions show similar patterns for the virtual water flows related to trade crop products. For the virtual water flows related to trade in animal products, this is slightly different. The USA, Canada, WEU, ANZ, EEU, FSU, CAM, SAM and CHI are net virtual water exporters and JPK, MDE, SAS, SEA, NAF and SSA are net virtual water importers regarding trade in animal products.

Table 5.5. Net virtual water import per region (Gm^3/year). 'A' refers to the net virtual water import related to agricultural products, 'I' to the net virtual water import related to industrial products and 'T' to the total net virtual water import.

	2000			S1			S2			S3			S4		
	A	I	T	A	I	T	A	I	T	A	I	T	A	I	T
USA	-117	27	-91	-377	92	-284	-350	48	-303	-101	57	-44	-101	39	-62
Canada	-42	-1	-43	-43	4	-39	-48	1	-47	-37	2	-35	-31	2	-29
WEU	59	43	102	3	101	104	6	60	66	42	70	112	24	38	61
JPK	90	9	99	89	22	111	89	11	100	55	15	71	43	9	52
ANZ	-72	3	-70	-140	5	-134	-154	3	-151	-102	4	-97	-82	2	-80
EEU	-8	-2	-10	-59	46	-13	-63	3	-60	-46	11	-35	-36	15	-21
FSU	-9	-34	-43	-183	-198	-381	-200	-77	-277	-150	-109	-259	-119	-56	-174
MDE	20	5	25	416	50	465	402	14	416	261	30	291	198	11	209
CAM	14	3	18	-127	41	-86	-117	11	-106	-83	23	-60	-59	12	-48
SAM	-174	1	-173	-1,695	34	-1,661	-1,736	6	-1,730	-1,007	15	-992	-801	10	-792
SAS	232	-8	224	1,056	14	1,070	1,117	-12	1,105	625	-29	596	509	7	515
SEA	-191	-12	-203	-146	-33	-179	-149	-16	-165	-140	-25	-166	-102	-11	-113
CHI	116	-38	78	-171	-244	-415	-152	-66	-218	-101	-103	-204	-63	-97	-159
NAF	60	0	60	66	14	80	84	3	87	47	11	59	46	3	49
SSA	3	1	4	1,249	20	1,269	1,223	3	1,226	720	12	732	564	6	569
RoW	21	3	24	60	31	92	49	8	56	15	14	29	10	11	21

The net virtual water flows related to industrial products in 2050 have a completely different structure. The USA, Canada, WEU, JPK, ANZ, EEU, MDE, CAM, SAM, NAF and SSA are the virtual water importers and FSU, SEA and CHI are net virtual water exporters related to trade of industrial products in all scenarios. SAS is a net virtual water importer in S1 and S4 and a net virtual water exporter in S2 and S3 regarding trade of industrial products. Most of the virtual water export related to industrial products comes from considering industrial products. In all regions, both net virtual water imports and exports are the highest in the S1 scenario regarding trade of industrial products as this scenario foresees the highest GDP increase and trade liberalization. Interregional virtual water trade related to industrial products decreases from S2 to S4. The decrease in S2 is due to increased self-sufficiency among the regions and the decrease in S3 and S4 is mainly due to improvements in water use efficiency and wastewater treatment in the industry sector.

Regarding interregional blue virtual water flows, the USA, ANZ, FSU, CAM, SAM and CHI are the net exporters and Canada, JPK, SAS and SSA are the net importers in all scenarios and in 2000. Despite being a net blue virtual importer in 2000, WEU becomes a net blue virtual water exporter in S2 and S4. NAF, a net blue virtual water importer in 2000, becomes a net blue virtual water exporter in S1 and S2. In all scenarios, the biggest net blue virtual water importers are SSA and SAS, whereas the biggest net blue virtual water exporters are SAM and CHI.

CHI and FSU are the biggest net virtual water exporting regions in terms of the grey component. Other net exporting regions are Canada, SEA, SAM and ANZ, for all scenarios. The USA, WEU, JPK, MDE, CAM, SAS, NAF and SSA are the net grey virtual water importing regions in all scenarios. EEU is a net importer of grey virtual water in S1, S3 and S4 but a net exporter in S2.

5.3.3 Water footprint of consumption

The WF of consumption in the world increases by +130% relative to 2000 for the S1 scenario. It increases by +175% in S2, +30% in S3 and +46% in S4 (Table 5.6). The high increase in the WF of consumption for S1 and S2 can, for a significant part, be explained by increased meat consumption. When we compare trade liberalization (S1 and S3) to self-sufficiency scenarios (S3 and S4), it is observed that trade liberalization decreases the WF of consumption globally.

The WF of consumption increases significantly for the regions SSA and MDE in all scenarios. The biggest change is observed in SSA with an increase by +355% in S1, +531% in S2, +181% in S3 and +262% in S4. MDE is the region with the second highest increase: +207% for S1, +294% for S2, +106% for S3 and +146% for S4.

The USA, Canada, ANZ, CAM, SAM, EEU, SAS, SEA and NAF are the other regions with a higher WF of consumption in 2050 relative to 2000. WEU, JPK, FSU and CHI have a higher WF of consumption in S1/S2 and a lower in S3/S4 relative to 2000. Population growth and dietary preferences are the two main drivers of change determining the future WF of consumption. In many regions of the world, S2 shows the highest WF of consumption as it has the largest population size with high-meat content diets. S4 shows higher WF values than S3 due to larger population size in S4 compared to S3.

The largest component of the total WF of consumption is green (67-81% per scenario), followed by grey (10-20%) and blue (7-13%). Consumption of agricultural products has the largest share in the WF of consumption, namely 85-93% for all scenarios. The share of domestic water supply is 2-3% and of industrial products 4-13%.

The WF of consumption of agricultural products is 112%, 180%, 18% and 38% higher in 2050 than 2000 in S1, S2, S3 and S4, respectively. SSA and MDE show the highest increase in all scenarios. WEU, JPK, EEU, CHI and FSU demonstrate increases in WF of consumption in S1/S2 and decreases in S3/S4 compared to 2000. S2 is the scenario with the highest WF related to consumption of agricultural products in all regions and S3 shows the lowest values among all scenarios.

The main driver of the WF of domestic water supply is population size. The scenario with the highest population projection, S2, has therefore the highest WF related to domestic water supply. S3 has the lowest values as it has a relatively low population size and a reduced WF per household. The regions that show reduction in WF of domestic water supply in S1, have population sizes lower than 2000. The reductions in S3 are due a combination of lower estimates of population and reduced per capita domestic water use. Regarding the WF of consumption of industrial products, all regions show a significant increase compared to 2000, in all scenarios.

Table 5.6. Percentage change of the WF of consumption relative to 2000. 'A' refers to the WF of agricultural products, 'D' refers to the WF domestic water supply, 'I' refers to the WF of industrial products and 'T' refers to the total WF.

Region	S1				S2				S3				S4			
	A	D	I	T	A	D	I	T	A	D	I	T	A	D	I	T
USA	29	24	112	41	83	57	69	80	29	-1	50	30	39	12	28	36
Canada	48	26	95	54	91	58	52	83	5	1	55	13	14	13	38	18
WEU	19	-3	112	28	52	22	65	52	-27	-23	52	-19	-24	-13	12	-20
JPK	11	-20	113	19	39	1	50	38	-36	-36	58	-26	-29	-28	15	-25
ANZ	172	40	107	171	201	77	62	199	20	12	73	20	5	26	13	5
EEU	12	-24	1024	143	45	0	285	75	-47	-39	438	17	-41	-30	419	20
FSU	6	-18	975	61	39	10	268	51	-44	-34	366	-20	-37	-24	340	-15
MDE	198	44	720	207	309	88	229	294	99	15	436	106	153	32	152	146
CAM	100	21	865	115	165	63	264	163	9	-3	490	20	24	13	292	30
SAM	117	24	722	126	181	66	204	177	21	-1	370	27	29	15	231	32
SAS	128	38	1206	143	214	85	313	212	27	11	1399	49	55	28	676	64
SEA	96	32	769	117	160	76	169	156	2	6	317	13	16	22	338	27
CHI	79	-12	1391	113	117	16	205	116	-29	-29	346	-18	-25	-19	771	-3
NAF	65	43	811	81	122	90	298	125	25	14	881	45	50	32	171	52
SSA	353	122	1415	355	538	183	334	531	179	78	969	181	263	101	486	262
RoW	212	-9	893	240	274	11	211	259	37	-27	366	52	51	-20	400	67
World	112	18	596	130	180	55	157	175	18	-6	308	30	38	8	259	46

Figure 5.5 shows the contribution of different consumption categories to the total WF of consumption for 2000 and for different scenarios. Consumption of cereals has the largest share (26%) in the total WF in 2000. Other products with a large share are meat (13%), oil crops (12%), poultry (10%), vegetables and fruits (8%) and dairy products (8%). Meat consumption becomes the major contributor to the WF of consumption in S1 and S2 (19-20%). Oil crops, vegetables, and fruits are the other consumption categories that have a

large contribution to the total WF of consumption in S1 and S2. The share of cereals decreases to 19% in S2 and to 17% in S1. Cereal consumption has the largest share (30%) in S3 and S4, which are characterized by low meat content diets. Oil crops follow cereals with 16%. The share of meat consumption decreases in these scenarios to 13%. Consumption of industrial products becomes another significant contributor in S3 and S4 (7%).

Cereals are the largest contributor to the blue WF of consumption in all scenarios. Its share is 25% in S1 and S2, and 39% in S3 and S4. Cereals are followed by vegetables and fruits in S1 and S2 (17%) and by oil crops for S3 and S4 (14%). Other product groups with a large share in the blue WF of consumption are meat, poultry, dairy products and sugar crops. The grey WF of consumption is dominated by industrial products and domestic water supply in all scenarios. The share of industrial products in the grey WF of consumption increases to 36% in S1 and S2 and 43% in S3 and S4, while it is 28% in 2000. The WF related to domestic water supply is the second largest contributor to the grey WF of consumption, with 18% for all scenarios.

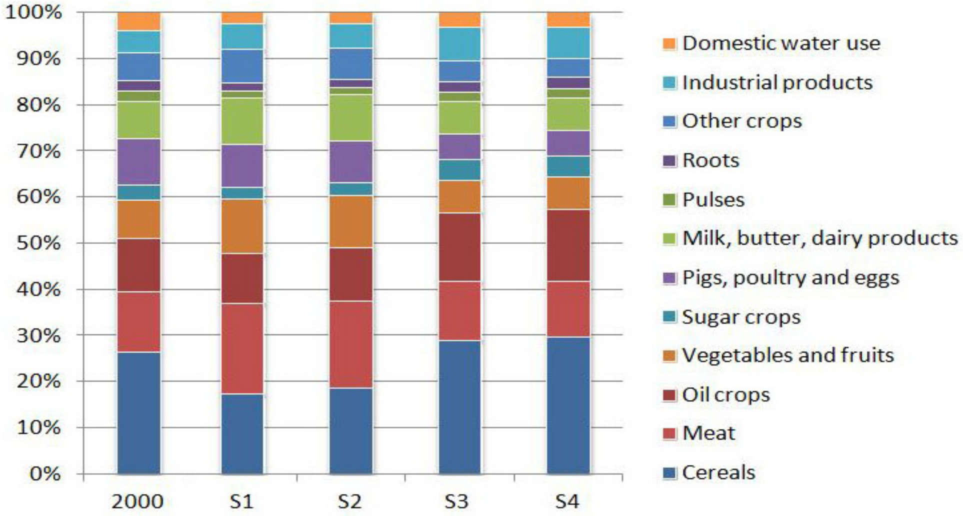

Figure 5.5. The contribution of different consumption categories to the total WF of consumption in the world.

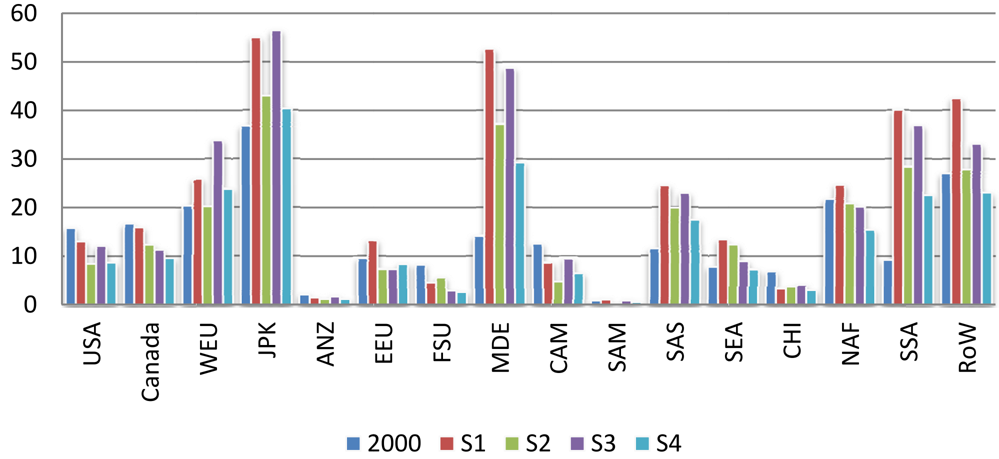

Figure 5.6. The share of the external water footprint of consumption in the total WF of consumption (%).

The share of the external WF of consumption in the total is given in Figure 5.6. Regions with large external WFs apparently depend upon freshwater resources in other regions. The regions with a high share of external footprint in 2000 like JPK and MDE increase their dependency on external water resources in 2050 significantly. For example, the share of the external WF in JPK will go up to 55% in S1 and to 56% in S3, in which trade is relatively liberalized compared to 2000. Our scenarios show that WEU, JPK, MDE, SAS, SEA and SSA increase their share of external WF while the other regions decrease their dependencies. The regions with increased production, like the USA, Canada and ANZ, decrease their external WF of consumption. In the scenarios with increased self-sufficiency, S2 and S4, the share of the external WF of consumption in the total WF of consumption is lower than other two scenarios, S1 and S3, which are characterized by trade liberalization.

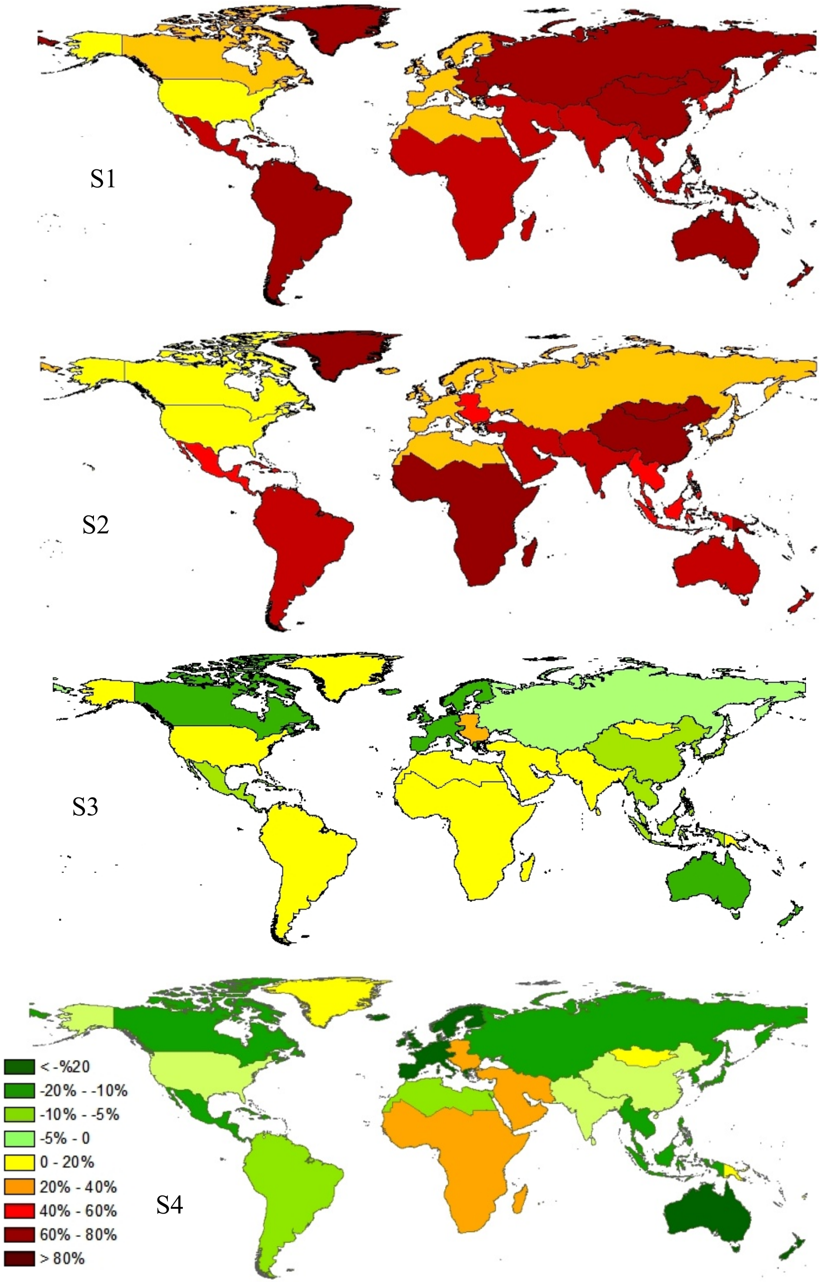

Figure 5.7. Percentage change of the WF of consumption per capita relative to 2000.

Figure 5.7 shows the change in the WF of consumption per capita per region for different scenarios relative to 2000 volumes. The world average WF of consumption per capita increases by +73% in S1, +58% in S2, -2% in S3 and 10% in S4 compared to 2000 volumes. All the regions increase their WF of consumption per capita in S1 and S2 compared to 2000. Canada, WEU, JPK, FSU, CAM, SEA, ANZ, CHI decrease their WF of consumption per capita in S3 compared to 2000 The other regions have a higher WF of consumption per capita in S3 than 2000. Most of the regions have lower WFs of consumption per capita in S4 than 2000 except EEU, MDE and SSA. The regions with relatively low meat consumption in 2000 experience the biggest change in S1 and S2, which assume western meat diet patterns in 2050. SSA is a good example for this, where per capita WF of consumption increases by +92% in S2. The change in the regions with high meat diet in 2000 already (the USA, Canada and WEU) is relatively lower than other regions in S1 and S2. A decrease is observed in S3 and S4 in these regions due to reduction in consumption of animal products except USA in S3. The reason of the increase in per capita WF of consumption in the USA in S3 is increased biofuel consumption. In the year 2000, the USA has the highest WF per capita in the world. Other regions with a high per capita WF of consumption are Canada, ANZ, FSU and WEU. In 2050, for the S1 and S2 scenarios, EEU has the highest WF per capita and is followed by the USA, FSU and Canada. WEU goes down in the ranking and has a lower WF of consumption per capita than the average of the world in 2050. The regions with higher WF of consumption per capita than the world average in 2000 also have higher values in S3 and S4, except WEU. The regions with relatively low WFs will continue to have lower values per capita in all scenarios (SEA, CHI, and SAS). Among the scenarios, S1 demonstrates the highest WF of consumption per capita and S4 shows the lowest.

5.4 The water footprint of Europe in 2050

In this section, we examine the WF scenarios for the two European regions (WEU and EEU) in more detail and zoom in to the country level. We estimate the WF of production and consumption per nation and per scenario inside Europe. In addition, we address the virtual water flows between Europe and the other regions of the world and the international virtual water flows within Europe.

5.4.1 Water footprint of production

The total WF of production in WEU increases by +12% in S1 and +42% in S2 relative to 2000 values. It decreases 36% in S3 and 29% in S4. The green WF of production becomes 17% and 48% larger in S1 and S2 and 38% and 32% smaller in S3 and S4 compared to 2000. The blue component changes in a similar way: increases by 9 and 35% in S1 and S2 and decreases by 11% in S3 and 1% in S4 (Figure 5.8). The grey component decreases in S1, S3 and S4 by 6, 40, 30% respectively, and increases by 22% in S2.

The WF of agricultural production in WEU increases by 19% in S1 and 51% in S2 and falls by 34 and 28% in S3 and S4 compared to 2000. The industrial WF of production in WEU decreases in all scenarios. The WF of domestic water supply reduces in S1, S3 and S4 but increases in S2 compared to 2000.

EEU increases its WF of production by +150% and +107% in S1 and S2 compared to 2000, respectively. The increase is lower in S3 and S4 than in the other scenarios, but volumes are 36% and 31% higher than in 2000, respectively. The grey WF of production in EEU shows the biggest growth: 448% in S1, 174% in S2, 197% in S3 and 179% in S4. The blue WF of production increases significantly as well: 231% in S1, 94% in S2, 93% in S3 and 81% in S4. Increases can also be seen in the green WF of production, which is 51% and 86% larger than 2000 in S1 and S2, respectively. In S3 and S4, the green WF of production decreases (18-19% lower than 2000).

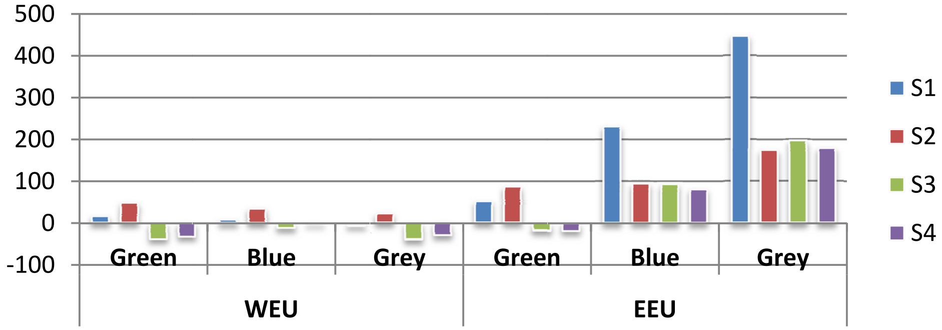

Figure 5.8. Percentage change in the WF of total production in WEU and EEU relative to 2000.

The WF of industrial production in EEU in S1 becomes 8 times higher than in 2000. The less drastic but still large increase is also detected in the other scenarios. The WF related to agricultural production becomes larger in S1 and S2, by 50% and 85%, respectively. It stays below the 2000 volumes in S3 and S4. The WF of domestic water supply remains on the value of 2000 in S2 and decreases by around 24-39% for S1, S3 and S4.

Among the agricultural products, the WF related to meat production has the largest share (28%) in the total for S1 and S2 in WEU. The share of meat production decreases to 19-22% in S3 and S4. Oil crops and cereals increase their share in the total WF of production in S3 and S4 partly due to the high demand for biofuel by WEU. The WF of meat production shows the biggest increase in S1 and S2 but it decreases 20% in S3 and S4 compared to 2000. The WF of vegetable and fruit production increases largely in S1 and S2 and decreases by 20%and 30% in S3 and S4 compared to 2000. For most of product groups, the WF of production increases in S1/S2 and decreases in S3/S4. The total WF of oil crop and sugar crop production increases in S2 and S4 and decreases in S1 and S3, compared to 2000.

The WF of agricultural production increases notably in EEU in S1 and S2 for all product groups. The WFs related to the production of meat, dairy products, vegetables and fruits multiply more than two times in S1 and S2. However, the total WF of production for these product groups reduces by 30% in S3 and S4. The total WF of sugar crop and oil crop production increases in S1, S2 and S4 compared to 2000. The increase in the overall WF of agricultural production is the highest in S2 because of the large population size and high meat content diet in this scenario.

On national level, Eastern European countries like Poland, Hungary, Bulgaria and Romania become important producers and significantly increase their WF of consumption in S1 and S2 compared to 2000 (Figure 5.9). The countries with the highest WF of production in 2000, like France and Spain, continue to have the largest WF of production in 2050. A shift from Southern Europe to Northern Europe is observed in the WF of cereal production. Norway, Luxembourg, Iceland, Cyprus and Malta have the highest increase of WF of production in S1 and S2 compared to 2000.

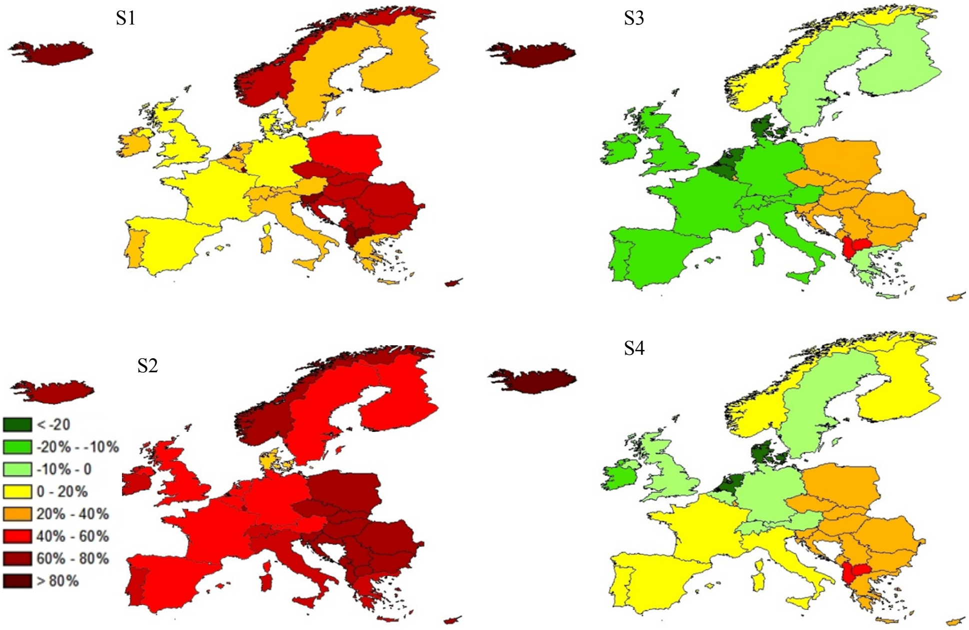

Figure 5.9. Percentage change of the WF of total production relative to 2000.

All Eastern European countries have a higher WF of production in S3 and S4 relative to 2000 although the increase (around 30%) is smaller than the increases in the WF of production observed in S1 and S2. All of the WEU countries decrease their WF of production in S3 compared to 2000, except Cyprus, Malta, Iceland and Norway. A reduction in WF of production is seen in the Netherlands, Belgium, Sweden, Germany, the UK, Ireland, Austria, Switzerland and Denmark in S4 compared to 2000. Spain and Italy, two counties with a large WF of production in 2000 in Europe, decrease their WF of production relative to 2000 only in S3 among all scenarios. Low-meat content diets and a shift of production to Central and Eastern Europe are the main reasons for this. Among the WEU countries, the Netherlands and Denmark have the highest reduction in the total WF of production compared to 2000, in S3 and S4. France reduces its WF of production in S3 but increases in S4 compared to 2000. Germany has a lower WF of production in S3 and S4 compared to 2000.

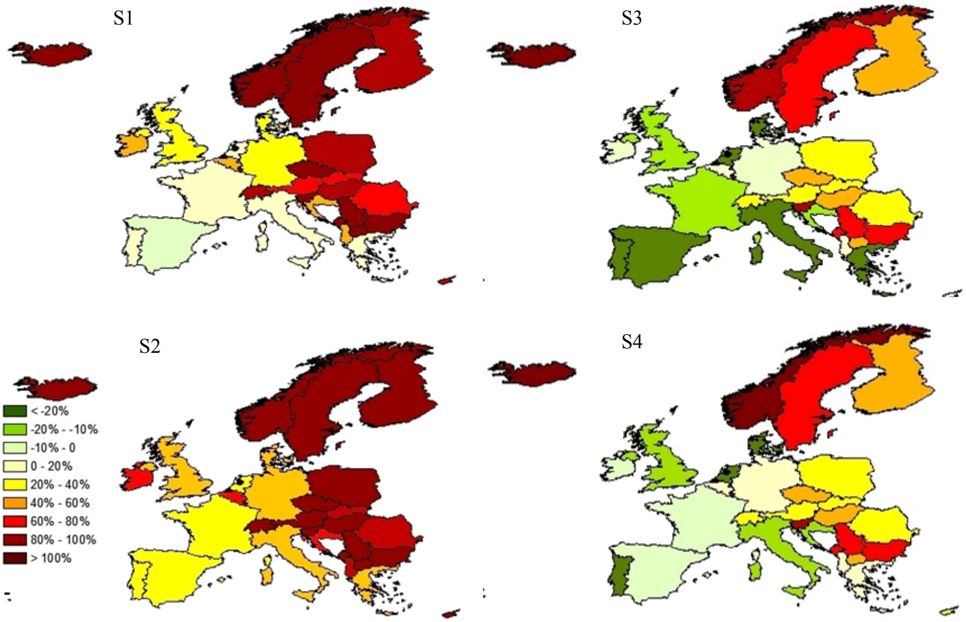

Figure 5.10. Percentage change of the blue WF of production relative to 2000.

The small island countries in Europe, Cyprus and Malta, increase their blue WF of production in S1 and S2 significantly (two and six times higher than 2000). These countries already experience high blue water scarcity so scenarios S1 and S2 will be very problematic for these countries. The blue WF of production in Malta increases significantly in S3 and S4 as well. Spain, another country with large water scarcity, decreases its blue WF of production by 3% in S1, 27% in S3, 5% in S4 but it increases its blue WF of production by 32% in S2. Italy, Portugal, Denmark, France, Ireland, the Netherlands and the UK have higher blue WFs of production in S1 and S2 than 2000 and lower blue WFs of production in S3 and S4 than 2000. Austria, Finland, Norway, Iceland, Sweden, Belgium, Switzerland and Luxembourg increase their blue WF of production in all scenarios (Figure 5.10).

Most of the EEU countries double their blue WF of production in S1 and S2. They also have higher blue WF of production in S3 and S4, except Croatia and Bosnia and

Herzegovina. Serbia, the Czech Republic, Slovenia and Macedonia have the highest increase in blue WF of production in EEU.

5.4.2 Virtual water flows between countries

WEU is a net virtual water importer in 2000 (Figure 5.11). It remains a net virtual water importer; however, it decreases its net virtual water import in S2 and S4 compared to 2000. It increases its net virtual water import by +2% in S1 and +10% in S3. The reduction in net virtual water import by WEU is -35% in S2 and -40% in S4. The net virtual water imports to WEU were mainly from SEA, SAM, FSU, CHI and SSA in 2000. The virtual water import from SAM increases by around +200% in S1, S2 and S3 and +120% in S4, which makes SAM the biggest virtual water exporter to WEU in 2050. Although SEA has a large net virtual water export to WEU in 2050, its net virtual water export to WEU decreases by -35% for S1, S2 and S3 and -55% for S4. The net virtual water imports from Canada, EEU and ANZ decrease as well, more than -50% in all scenarios. The net virtual water import from the USA increases more than 10 times in 2050 for all scenarios but remain relatively small compared to the net virtual water exports from other regions. The virtual water import volume from FSU increases by 210% in S1, 100% in S2 and S3 but decreases by 4% in S4. WEU increases its net virtual water import from China by +410% in S1 and more than +100% in S2, S3 and S4. Being net virtual water exporters to WEU in 2000, SSA and MDE become net virtual water importers from WEU in 2050 for all scenarios. WEU is a net virtual water exporter to SAS, MDE, NAF, SSA and JPK in 2050. The largest net virtual water export is to SSA in all scenarios, followed by SAS and MDE. The net virtual water exports by WEU to SSA increases significantly in 2050 due to increased trade of animal products.

EEU, a net virtual water exporter in 2000, remains a net virtual water exporter in 2050. It considerably increases its net virtual water export, by +100% S4 up to +500% in S2 compared to 2000 (Figure 5.12). Its virtual water exports are higher than its imports from all the regions except the USA, Canada, CHI, SAM, FSU, CAM and ANZ in 2050. The largest net virtual water flow from EEU is to SSA, MDE and SAS in 2050. Being a net virtual water exporter to CHI and FSU in 2000, EEU becomes a net virtual water importer from these regions in 2050. Among the scenarios, net virtual water import by EEU is the highest in S1 and lowest in S3.

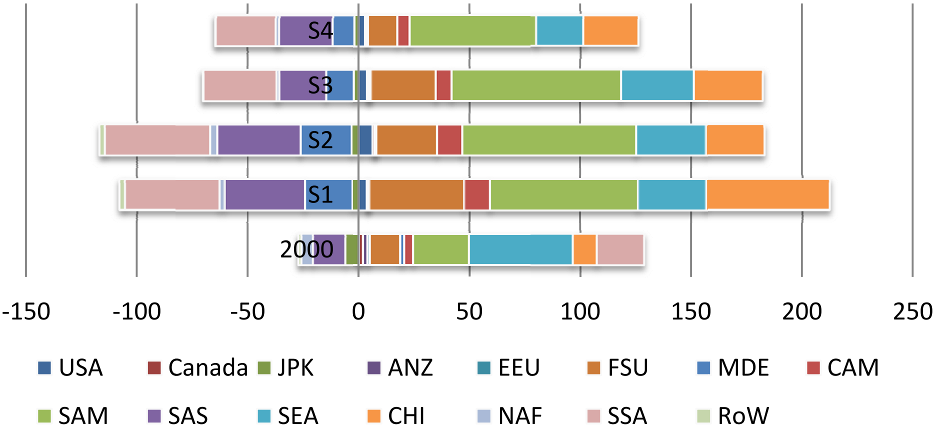

Figure 5.11. Net virtual water import by WEU specified by region (Gm^3/year).

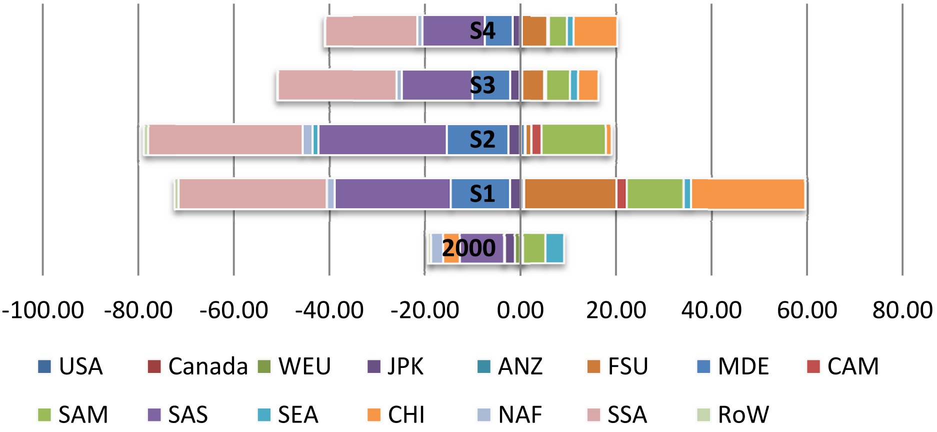

Figure 5.12. Net virtual water import by EEU specified by region (Gm^3/year).

Figure 5.13 shows the net virtual water flows from/to WEU and EEU by their green, blue and grey components. WEU is a net blue virtual water importer in 2000. In

2050, WEM becomes a net blue virtual water exporter in S2 and S4. By 2050, most of the net blue virtual water flows from WEU are to SSA, SAS and MDE and net blue virtual water imports to WEU are from SAM, the USA and ANZ. From the green water perspective, WEU is a net virtual water importer in all scenarios. As for grey component, WEU continues to be a net importer in 2050 and increases its net virtual water import by +143% in S1, +29% in S2, +74% in S3. EEU is a net virtual water exporter in terms of green and blue components in 2050. It is a net grey virtual water importer in S1, S3 and S4 and exporter in S2. The green component has the biggest share in net virtual water exports from EEU.

The net virtual water import to WEU is mainly related to crop products and industrial products. The region is a net virtual water exporter considering animal products in 2050 (Figure 5.14). The net virtual water export related to animal products increases very substantially in EEU as well. Although EEU is a net virtual water exporter in 2000 regarding all product groups, it becomes a net virtual water importer related to industrial products in 2050.

The virtual water export from EEU to WEU is larger than imports, therefore a net virtual water flow from EEU to WEU is observed in 2000. This continues towards 2050 but the net virtual water import by WEU from EEU is reduced largely in S1, by -90%.

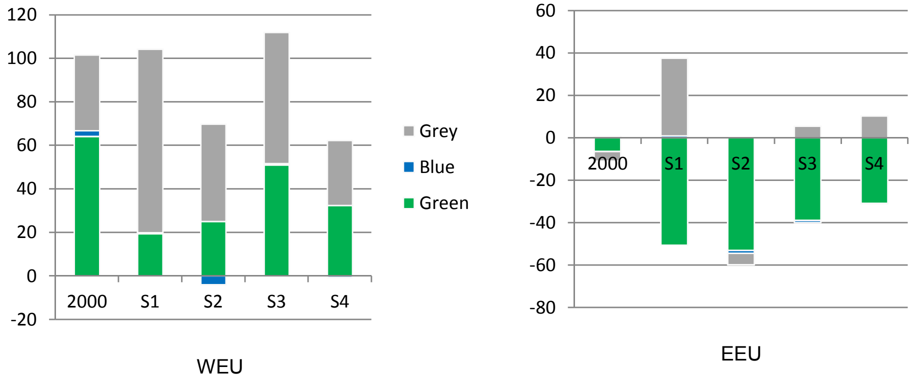

Figure 5.13. Net virtual water import by WEU and EEU specified by green, blue and grey components (Gm^3/year).

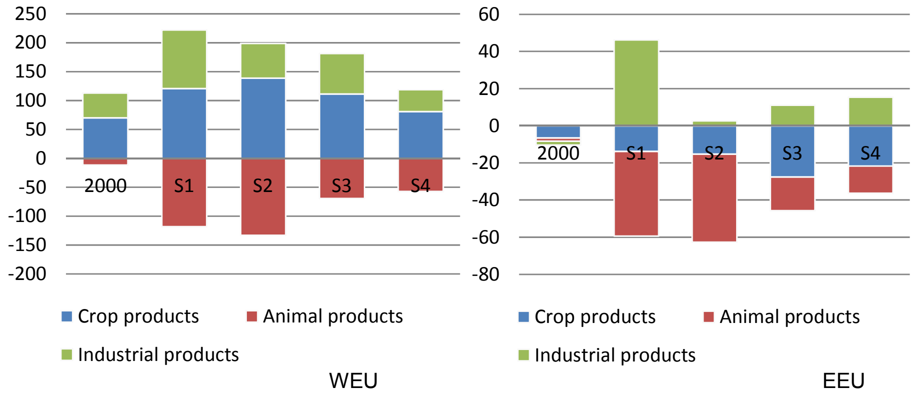

Figure 5.14. Net virtual water import by WEU and EEU specified by commodity group (Gm^{3}year).

Figure 5.15 shows net virtual water imports per nation in Europe for 2000 and four scenarios. All WEU countries are net virtual water importers in 2000. Countries like France, Spain, Ireland, Denmark, Greece and the Netherlands become net virtual water exporters for scenarios S1 and S2. In particular, the change in France is quite big. The UK, Italy, Portugal, Sweden, Norway, Finland, Germany, Austria, Belgium, Switzerland, Malta, Cyprus and Iceland remain net virtual water importers in S1 and S2. The net virtual water flow changes direction for some countries in S3. Spain and the Netherlands are net importers in S3. France, Denmark, Greece, and Ireland are net virtual water exporters in S3 and S4.

Romania, Bulgaria, Serbia and Montenegro are net virtual water exporters in 2000 and stay so in 2050. Poland, the Czech Republic and Hungary are net virtual water importers in 2000 and become net virtual water exporters in 2050. Slovakia, Macedonia, Bosnia and Herzegovina, Croatia and Albania are net virtual water importers in 2000 and 2050. Slovenia is a net virtual water exporter in S1 and S2 and a net virtual water importer in S3 and S4.

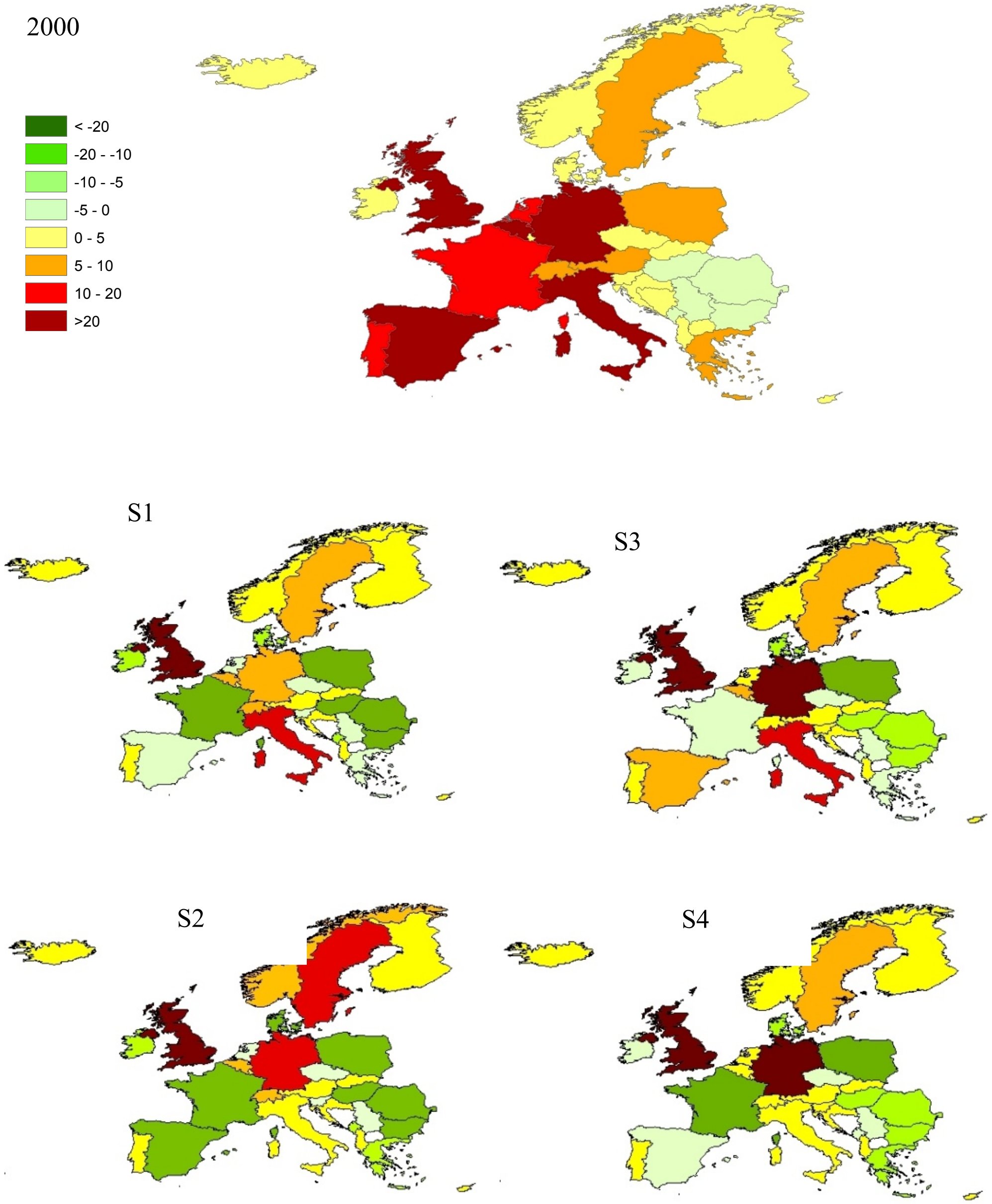

Figure 5.15. Net virtual water import per European country (Gm^{3}year).

5.4.3 Water footprint of consumption

The total WF of consumption in WEU increases by 28% and 52% in S1 and S2 compared to 2000. The WF of consumption in WEU decreases by -19% in S3 and -20% in S4. EEU increases its WF of consumption in all scenarios compared to 2000, by +143% in S1, +75% in S2, +17% in S3 and +20% in S4. The WF of consumption per capita in WEU increases by +30% in S1 and +22% in S2 and decreases by -18% in S3 and -28% in S4. EEU has a higher WF of consumption per capita in 2050 than 2000 with an increase of 186% in S1, 57% in S2, 38% in S3 and 23% in S4. Approximately 70% of the total WF of consumption in WEU is green, in both 2000 and 2050. It is followed by the grey and blue components with the share of 20% and 10%, respectively. The share of green WF of consumption in total in EEU decreases from 73% in 2000 to 34% in S1, S3 and S4. The share of grey WF of consumption in EEU increases from 23% in 2000 to 60% in S1, S3 and S4. The share of green, blue and grey components in total WF of consumption in EEU in S2 is same as the shares in 2000.

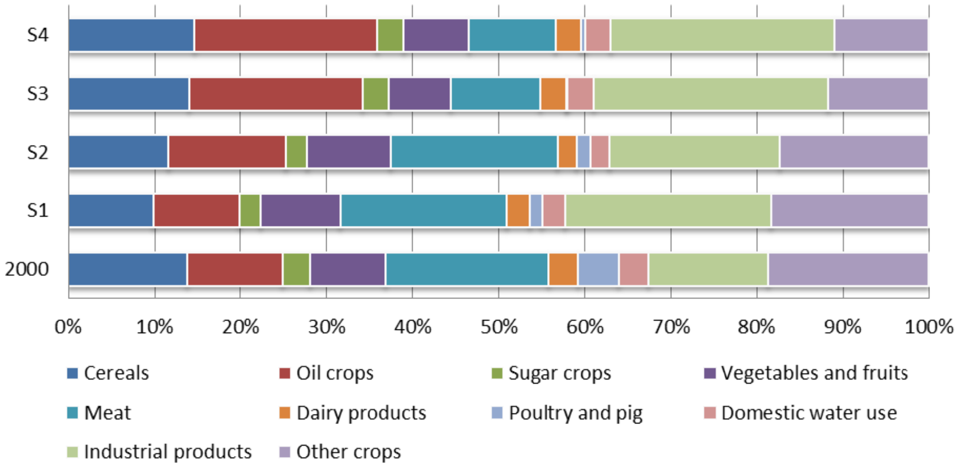

Figure 5.16. The composition of the total WF of European consumption by commodity.

The WF of consumption per commodity group in Europe is given in Figure 5.16. Meat and cereals are the product groups with the biggest share in the WF of consumption in

2000. The share of meat consumption decreases in S1 and S2. It falls down considerably in S3 and S4 scenarios. The WF related to the consumption of industrial products doubles its share in 2050 compared to 2000. Other commodities with a large share in total WF of consumption in 2050 are cereals and oil crops. Especially the share of oil crops significantly increases in S3 and S4, due to drastic biofuel expansion.

The blue WF of consumption in Europe is mainly due to industrial products in 2050 (Figure 5.17). Vegetables and fruits are the second biggest contributor to the total blue WF of consumption in 2050 (14-16%). The share of oil crops in total blue WF of consumption increases with 9% in S1, 12% in S2, 14% in S3 and 20% S4. The share of blue WF of meat consumption in total blue WF of consumption is 12% in S1 and S2, 8% in S3 and 7% in S4. Other product groups with large share in total blue WF of consumption are dairy products, domestic water supply and cereals in all scenarios.

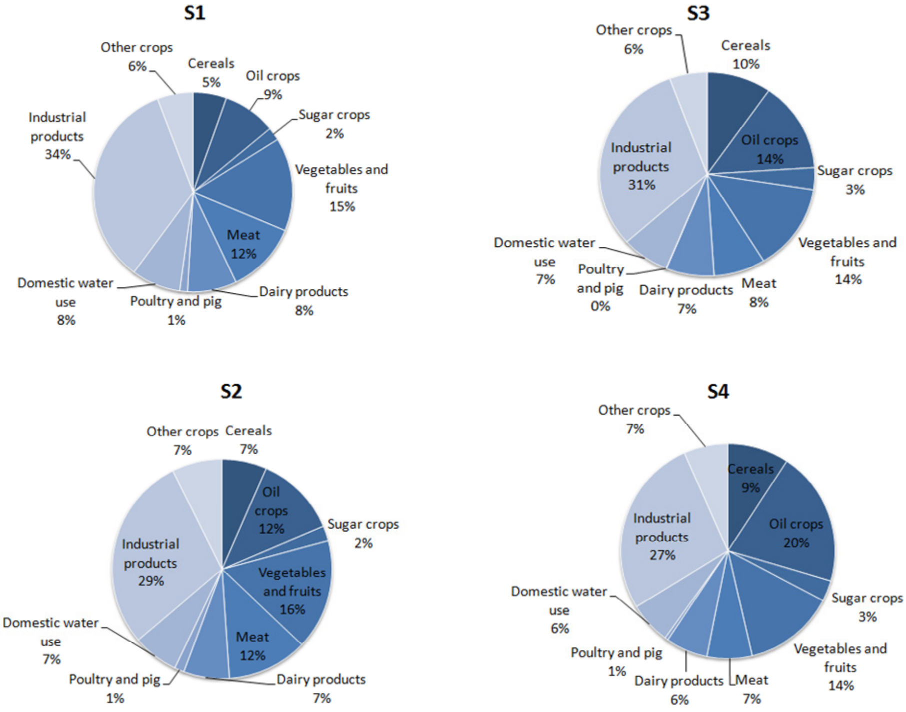

Figure 5.17. The composition of the blue WF of European consumption by commodity.

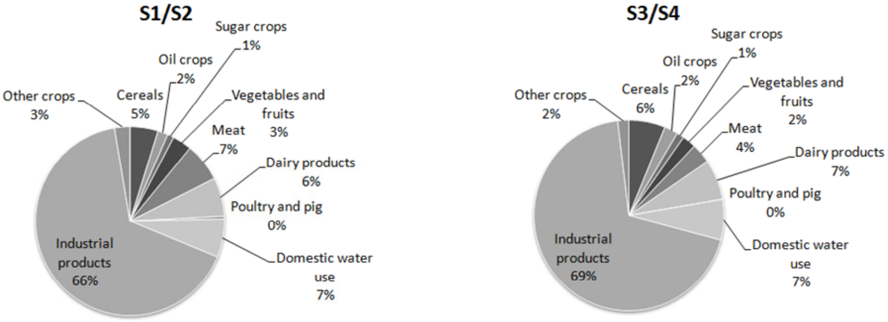

Figure 5.18. The composition of the grey WF of European consumption by commodity.

The grey WF of consumption is mainly from industrial products, with the share of 66% in S1 and S2 and 69% in S3 and S4. Domestic water supply is another big contributor to the total grey WF of consumption, 7% of the total grey WF of consumption in all scenarios. Other product groups with a large share in total grey WF of consumption are dairy products (6-7%), cereal (5-6%), meat (4-7%), vegetables and fruits (2-3%). The composition of the grey WF of consumption does not differ much from scenario to scenario (Figure 5.18).

The change in WF of consumption per capita relative to 2000 for the nations of Europe is shown in Figure 5.19. All WEU countries have a higher WF of consumption per capita in S1 and S2 than 2000, except Denmark, Ireland, Luxembourg and the Netherlands. Belgium, Sweden, Cyprus, Iceland and Malta have higher WF of consumption per capita in 2050 than 2000. Austria, France, Greece, Italy, Norway, Portugal, Spain, Switzerland and the UK decrease their WF of consumption in S3 and S4 compared to 2000. Italy, the Netherlands, Spain, Switzerland, Luxembourg and the UK reduce their WF of consumption per capita values by more than -20% in S4. Among WEU nations, Cyprus, Malta and Iceland significantly increase their WF of consumption per capita in S1 and S2. Spain has the highest WF of consumption per capita in 2000. In 2050, Malta has the highest WF of consumption per capita.

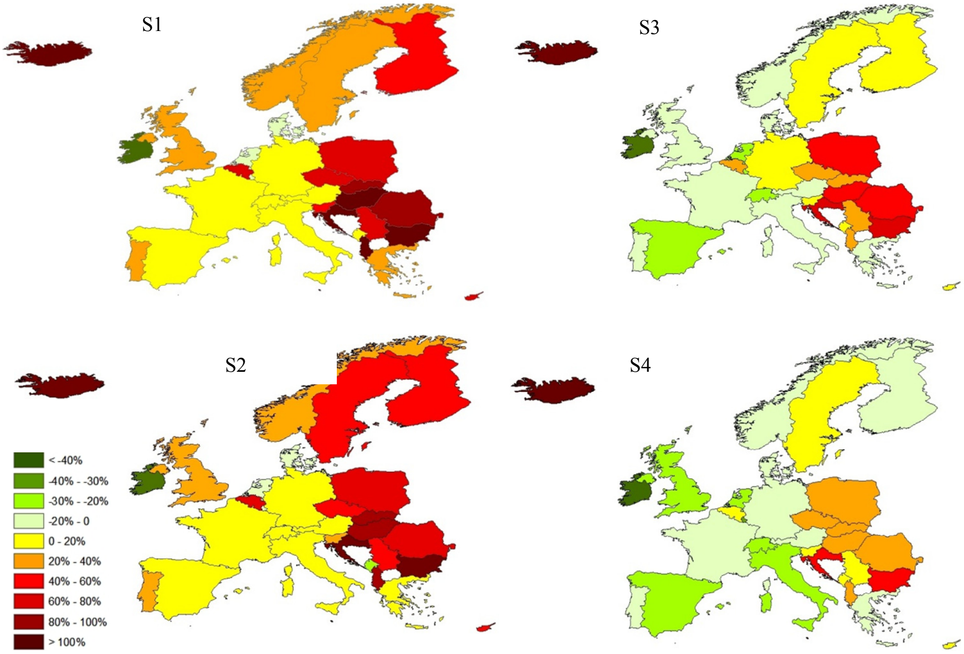

Figure 5.19. Percentage change of the WF of consumption per capita relative to 2000.

In 2050, EEU countries have a higher WF of consumption per capita than in 2000. Bulgaria, Hungary, Croatia, Macedonia and Bosnia and Herzegovina increase their WF consumption per capita by more than +100% in S1 and S2. Montenegro is the only country in EEU with a reduction in WF of consumption per capita in S2.

The share of external WF of consumption in total WF of consumption increases in WEU in 2050. However, these countries with a very high external WF consumption share in 2000 like the Netherlands (94%), Malta (90%) and Belgium (90%) significantly reduce this ratio below 50% in all scenarios. The UK, Switzerland and Luxembourg have an external WF of consumption share more than 60% in all scenarios. Spain significantly reduces its share of external WF of consumption in 2050. All of the EEU counties reduce the share of external WF of consumption in S2, S3 and S4.

5.5 Discussion and conclusion

This study is the first global water footprint scenario study. It explores how the water footprint of humanity will change towards 2050 under four alternative scenarios, which differ from each other in terms of specific trajectories for the main drivers of change. Although we included the major drivers of change in our analysis, some of them were kept outside the scope of this study. First, we excluded the impact of resource availability. The constraints related to water and land availability are only addressed implicitly in the production and trade scenarios. A future step would be to integrate such limitations explicitly. Climate change effects are partially addressed in our study. We implicitly included the impact of climate change on production and trade patterns, but we excluded CO_2 fertilization effects in yields and climate change effects on crop water use. Another limitation is that we assumed a homogeneous and single industrial sector in estimating the water footprint of industrial production and consumption.

Our analysis shows that water footprints can radically change from one scenario to another and are very sensitive to the drivers of change:

- Population growth: The size of the population is the major driver of change of the WF of production and consumption. The WF of production and consumption is the largest in the scenario in which the population projection is the highest (S2).
- Economic growth: The effect of economic growth is observed in terms of income levels and GDP changes. Increased income levels result in a shift toward high consumption of water intensive commodities. GDP growth significantly increases industrial water consumption and pollution. S1 has the highest WF of industrial production and consumption among all scenarios because it foresees the highest GDP.
- Consumer preferences: The diet of people strongly influences the water footprints of consumption and production. Diets with increased meat and dairy products result in very high water footprints in 2050 (S1 and S2 scenarios). In S3 and S4, the scenarios with low meat content, the total water footprint of consumption and production in the

world drastically decrease. This shows us that a reduction in humanity's water footprint is possible in 2050 despite population increase.

- Biofuel use: Existing plans related to biofuel use in the future will increase the pressure on water resources. The study shows that a high demand of biofuel increases the water footprint of production and consumption in the world and especially in Western Europe, the USA and Brazil.
- Importance of international trade: A reduction in water footprints is possible in 2050 by liberalization of trade (S1 versus S2 and S3 versus S4). Trade liberalization, on the other hand, will imply more dependency of importing nations on the freshwater resources in the exporting nations and probably energy use will increase because of long-distance transport.
- Climate change: Global agriculture production and trade structure will be affected by climate change. The production volumes will decrease in some parts of the world and will increase in others. The production changes across the world will affect the water footprint of production. In overall, our results show total water footprint of production of humanity will decrease because of climate change effects on global agricultural production. However, it does not result in similar change in all parts of the world. It will increase the water footprint of production in Europe, Australia and East Asia decrease the water footprint of production in the USA, Middle East and Russia. Evidently, climate change will also affect water availability and scarcity around the world differently and this should be combined with this information carefully.
- Technology: Technologic development directly affects water productivity, water use efficiency and wastewater treatment levels. Increased water productivity as a result of technological development result in reduction of the water footprint of consumption and production.

From the European point of view, this study shows that the most critical driver of change that affects future WF of production and consumption for Europe is consumption patterns. The WF of production and consumption in WEU increase in the 'high-meat' scenarios (S1 and S2) and decrease in the ‘low-meat’ scenarios (S2 and S3). In addition, extra demand created by biofuel needs put extra pressure on European water resources (S3 and S4). The European countries with a high external WF of consumption ratio in 2000 decrease their dependencies on foreign water resources (e.g. the Netherlands, Belgium and Luxembourg).

This study shows how different driver will change the level of water consumption and pollution globally in 2050. These estimates can form an important basis for a further assessment of how humanity can mitigate future freshwater scarcity. We showed with this study that reducing humanity’s water footprint to sustainable levels is possible even with increasing populations, provided that consumption patterns change. This study can help to guide corrective policies at both national and international levels, and to set priorities for the years ahead in order to achieve sustainable and equitable use of the world’s fresh water resources.

Appendix 5.1: Countries and regional classification

Region code	Region	Countries
1	USA	United States of America
2	Canada	Canada
3	WEU	Andorra, Austria, Cyprus, Denmark, Finland, France, Germany Greece, Iceland, Ireland, Italy, Malta, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, United Kingdom, Belgium, Luxembourg
4	JPK	Japan, Dem. People's Republic of Korea
5	ANZ	Australia, New Zealand
6	EEU	Albania, Bulgaria, Bosnia and Herzegovina, Hungary, Croatia, TFYR Macedonia, Czech Republic, Poland, Romania, Slovenia, Slovakia, Serbia Montenegro
7	FSU	Armenia, Azerbaijan, Belarus, Estonia, Georgia, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Republic of Moldova, Russian Federation, Tajikistan, Turkmenistan, Ukraine, Uzbekistan
8	MDE	Bahrain, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Qatar, Saudi Arabia, Syrian Arab Republic, Oman, Turkey, United Arab Emirates, Yemen, Occupied Palestinian Territory
9	CAM	Caribbean, El Salvador, Grenada, ,Mexico, , Nicaragua, Panama
10	SAM	Argentina, Bolivia , Brazil, Chile, Colombia, Ecuador, ,French Guiana, Guyana, Paraguay, Peru, Suriname, Uruguay, Venezuela
11	SAS	Afghanistan, Bangladesh, Bhutan, Sri Lanka, India, Maldives, Nepal, Pakistan
12	SEA	Brunei, Darussalam, Myanmar, Indonesia, Cambodia, Laos, Malaysia, Philippines, Timor-Leste, Singapore, Thailand, Viet Nam
13	CHI	China
14	NAF	Algeria, Egypt, Libyan Arab Jamahiriya, Morocco, Western Sahara, Tunisia
15	SSA	Angola, Botswana, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo, Benin, Equatorial Guinea, Djibouti, Gabon, Gambia, Ghana, Guinea, Côte d'Ivoire, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Niger, Nigeria, Guinea-Bissau, Eritrea, Zimbabwe, Réunion, Rwanda, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, Sudan, Swaziland, Tanzania Togo, Uganda, Burkina Faso, Ethiopia, Congo, Zambia, Mayotte
16	RoW	Other non-specified areas (Rest of the World)

Appendix 5.2: Population and GDP forecasts

Population

Region	Region	S1-2050	S2-2050	S3-2050	S4-2050
1	USA	357,007,000	452,394,000	357,007,000	403,100,000
2	CAN	38,845,000	48,791,000	38,845,000	43,641,000
3	WEU	385,569,000	487,475,000	385,569,000	434,634,000
4	JPK	119,338,000	151,811,000	119,338,000	134,930,000
5	ANZ	32,903,000	41,515,000	32,903,000	37,063,000
6	EEU	93,422,000	122,034,000	93,422,000	107,097,000
7	FSU	239,902,000	320,767,000	239,902,000	278,366,000
8	MDE	403,048,000	525,568,000	403,048,000	461,667,000
9	CAM	225,896,000	304,142,000	225,896,000	262,882,000
10	SAM	419,973,000	564,683,000	419,973,000	488,073,000
11	SAS	1,990,834,000	2,660,586,000	1,990,834,000	2,308,540,000
12	SEA	655,577,000	872,810,000	655,577,000	759,206,000
13	CHI	1,130,211,000	1,479,309,000	1,130,211,000	1,295,603,000
14	NAF	200,112,000	265,577,000	200,112,000	231,496,000
15	SSA	1,731,742,000	2,204,177,000	1,731,742,000	1,960,102,000
16	RoW	81,243,000	98,602,000	81,243,000	89,589,000
17	World	8,105,622,000	10,600,241,000	8,105,622,000	9,295,989,000

GDP (1990 US$ MEX)

Region	Region	S1-2050	S2-2050	S3-2050	S4-2050
1	USA	21758785042065	17355484996242	19249661687548	16414353161340
2	CAN	1853763940822	1446163121773	1836185439521	1634556518207
3	WEU	23553103572664	18374308098248	21125539816549	15553707375045
4	JPK	9082835848045	6430169278057	8424823206354	6141977795023
5	ANZ	948923321297	740344752629	988793402357	643490166991
6	EEU	3366254712014	1153188770022	2015141767763	1941334293422
7	FSU	10005897982675	3427752851389	5416984803691	5115675629960
8	MDE	12575743797432	5038190390666	10267041500486	4821689528756
9	CAM	7091959678872	2674606474631	5426717678644	3598373232136
10	SAM	15866432073256	5873001540866	11334363400416	7985386183870
11	SAS	12836624204768	4063470017500	18425511851559	9533839146457
12	SEA	10838071266980	3354806708623	6509907246729	6832038421202
13	CHI	25718590039554	5262355190158	9620976808823	18778528893685
14	NAF	4954364041239	2164826449829	6669075096881	1844179845178
15	SSA	13162859514781	3768938467049	11610784630915	6362618805968
16	RoW	8253990018825	2585651189853	4844943399150	5195770140139

Appendix 5.3: Coefficient for change in unit water footprint of agricultural commodities per region per scenario (α values)

	S1 & S2			S3 & S4		
Region	Blue WF	Green WF	Grey WF	Blue WF	Green WF	Grey WF
USA	0.80	1.00	1.00	1.00	0.80	0.80
Canada	0.80	1.00	1.00	1.00	0.80	0.80
WEU	0.80	1.00	1.00	1.00	0.80	0.80
JPK	0.80	1.00	1.00	1.00	0.80	0.80
ANZ	0.80	1.00	1.00	1.00	0.80	0.80
EEU	0.80	1.00	1.00	1.00	0.70	0.70
FSU	0.80	1.00	1.00	1.00	0.70	0.70
MDE	0.80	1.00	1.00	1.00	0.80	0.80
CAM	0.70	1.00	1.00	1.00	0.80	0.80
SAM	0.70	1.00	1.00	1.00	0.80	0.80
SAS	0.70	1.00	1.00	1.00	0.60	0.60
SEA	0.70	1.00	1.00	1.00	0.60	0.60
CHI	0.70	1.00	1.00	1.00	0.60	0.60
NAF	0.80	1.00	1.00	1.00	0.80	0.80
SSA	0.60	1.00	1.00	1.00	0.80	0.80
RoW	0.80	1.00	1.00	1.00	0.80	0.80

Appendix 5.4: Agricultural production changes in 2050 relative to the baseline in 2050

Region	Baseline relative to 2000 (%)	Percentage change relative to baseline 2050							
		TL1	TL2	A1B	A2	A1B+T1	A1B+TL2	A2+TL1	A2+TL2
USA	89	-0.41	-0.35	-9.20	-10.12	-9.40	-9.36	-10.31	-10.28
CAN	50	0.66	1.76	-10.04	-8.53	-9.53	-8.78	-7.99	-7.21
WEU	5	0.21	-0.41	4.30	4.83	4.73	4.19	5.27	4.72
JPK	6	-0.26	0.22	6.47	6.86	6.61	7.52	7.01	7.85
ANZ	67	1.48	1.49	6.95	9.49	8.40	8.41	10.90	10.93
EEU	33	-0.14	-0.24	2.59	2.29	2.49	2.43	2.18	2.12
FSU	79	-0.15	-0.18	-21.28	-20.42	-21.30	-21.28	-20.41	-20.39
MDE	93	0.11	0.08	-23.24	-16.81	-23.23	-23.22	-16.76	-16.75
CAM	139	-0.12	-0.19	-1.70	-2.70	-1.81	-1.89	-2.80	-2.88
SAM	248	0.21	0.16	-1.77	-1.81	-1.65	-1.76	-1.70	-1.80
SAS	84	-0.73	-0.76	-3.16	-2.17	-3.89	-3.84	-2.97	-2.93
SEA	101	0.01	0.04	-11.63	-12.28	-11.74	-11.68	-12.40	-12.34
CHI	31	0.20	0.37	11.18	9.04	11.54	11.88	9.36	9.68
NAF	110	0.12	-0.17	-8.90	-13.73	-8.91	-9.00	-13.73	-13.81
SSA	158	-0.29	-0.39	3.54	3.69	3.24	3.13	3.39	3.28
RoW	173	0.91	0.93	-3.58	-3.64	-2.82	-2.79	-2.89	-2.86

Source: Calzadilla et al. (2011a)

6 Understanding carbon and water footprints: similarities and contrasts in concept, method and policy response[5]

Abstract

The objective of this study is to analyse the origins and the characteristics of the carbon and water footprints in order to understand their similarities and differences and to derive lessons on how society and business can adequately build on the two concepts. We compare the two concepts from a methodological point of view and discuss response mechanisms that have been developed, with the hope that experiences in one field might be able to benefit the other.

The carbon and water footprint concepts were introduced about a decade ago, simultaneously, but independently from one another. The 'carbon footprint' concept has become popular over the past few years – since, more or less, 2005 – and is currently widely accepted and used by the public and media despite its lack of scientifically accepted and universally adopted guidelines: it describes greenhouse gas emission measurement from the narrowest to the widest sense. Several calculation methods and approaches for carbon footprint accounting have been proposed and are being used. Since about 2008, 'water footprint' has also become a popular term. Although the meaning and methodology of the water footprint were well defined in the scientific literature in the early stages of its inception, there is still an immense potential for less rigorous usage of the term, similar to the fate of the carbon footprint. The ambiguity around the concept of the carbon footprint could become a problem for the water footprint concept in the near future. By drawing lessons from the history and progress of the carbon footprint and understanding the development and mechanisms of carbon footprint assessment (both accounting and response formulation), we can draw lessons that may help reduce the risk that the water footprint will lose its strict definition, interpretation and usage.

In response to the increasing concern about climate change and global warming, governments, businesses and consumers are considering ways to reduce greenhouse gas

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[5] Based on Ercin and Hoekstra (2012b)

emissions. The two main response strategies are reduction and offsetting. *Reduction* refers to undertaking activities in a less carbon intensive way; *offsetting* refers to taking external actions to compensate for carbon footprints by means of some form of carbon capture or reduction elsewhere (by others). These strategies are applied and supported widely by business and government. However, two issues seriously challenge the effective reduction of humanity's carbon footprint. The first is the absence of a unique definition of the carbon footprint, making reduction targets and statements about carbon neutrality difficult to interpret, and leaving potential for developments to look better than they really are. The second problem is that existing mechanisms for offsetting leave room for creating externalities and rebound effects. In the case of the water footprint, the question of how to respond is still under debate, but it has been recognized that reduction and offsetting strategies can be distinguished here too. The terms 'water neutral' and 'offsetting' have been considered. The strategy of water offsetting may face the same problem as in carbon offsetting, but there is an additional problem: water footprints impact at specific locations and in specific periods of time, and offsetting can only be effective if the offsetting efforts relate to them.

Carbon footprint accounting has been promoted by companies, non-governmental organizations and private initiatives and has not primarily been driven by research. This situation has led to the concept having many definitions, methods of calculation and response formulations. Some companies are responding rapidly to formulate schemes to tout their carbon neutrality, but the response is often driven by the interest in brand and image – many businesses see benefits in using the carbon footprint as a marketing tool rather than as a tool to measure their contribution to climate change. Carbon accounting, labelling and meeting the requirements of reduction or offsetting schemes tend to become goals in themselves rather than supportive instruments to effectively mitigate climate change. Carbon offsets distract attention from the wider, systemic changes and collective political action required to tackle climate change. These insights can be helpful in the search for effective instruments that can contribute to a more efficient, sustainable and equitable use of the globe's water resources.

Global warming and reduction of greenhouse gas emissions are at the top of the environmental policy agenda today. However, the way in which the concept of the carbon footprint has been embraced and interpreted in all possible directions and the fact that reduction schemes are often ill-defined creates unnecessary additional challenges in effectively tackling environmental problems. We argue in this study that the weakness of offsetting in the case of the carbon footprint shows that applying both offsetting and neutrality in the water footprint cannot be effective. A more effective tool may well be direct water footprint reduction targets to be adopted by both government and business.

6.1 Introduction

The Earth's climate is changing as a result of anthropogenic activity since the start of the industrial revolution. There is growing scientific evidence that burning fossil fuels contributes to rising temperatures and extreme weather events (Mitchell et al., 2006; Rosenzweig et al., 2001; Solomon et al., 2007). The public and decision-makers have started to recognize the need for action to mitigate global warming (Goodall, 2007). Governments, policy-makers and businesses have been urged to seek ways to reduce greenhouse gas (GHG) emissions in response to growing interest and concern about climate change over the past two decades (Bo et al., 2008; Brenton et al., 2009; Courchene and Allan, 2008; Matthews et al., 2008). This brings the need to understand what activities drive GHG emissions and how they can be effectively reduced. The 'carbon footprint' (CF) concept has become a popular tool to estimate GHG emissions related to human activities (Moss et al., 2008; Wiedmann, 2009a; Wiedmann and Minx, 2007).

Climate change has received a lot of attention at international forums among politicians and business leaders in the past decade. Freshwater scarcity has recently become an important subject on the environmental agendas of governments and companies as well. Across the media, decision-makers and the public, there is much talk of a looming 'water crisis', which would have impacts on all sectors of the economy, but would primarily affect food security. Freshwater in sufficient quantity and of adequate quality is not only a prerequisite for human societies but also for natural ecosystems (Costanza and Daly, 1992). The unsustainable use of freshwater resources by humans is manifested all around the world in aquifers gradually becoming depleted, rivers running dry, and water quality deteriorating (Postel, 2000). Overexploitation of water resources for human activities affects societies but also jeopardizes the health of ecosystems. Therefore, there is a growing demand for new approaches and indicators in the field of water resources management that can help find the main drivers of unsustainability and identify solutions towards sustainable water use, satisfying increased demand for food, domestic water supply, and goods and services, but protecting vital ecosystems.

Understanding the consequences of human appropriation of freshwater resources requires an analysis of how much water is needed for human use versus how much is available, where and when (Hoekstra and Chapagain, 2008; Lopez-Gunn and Llamas, 2008). Uncovering the link between consumption and water use is vital to formulate better water governance. The term 'water footprint' (WF) was primarily formulated in the research context, to study the hidden links between human consumption and water use and between global trade and water resources management (Hoekstra, 2003). The concept helps us understand the relationships between production, consumption and trade patterns and water use and the global dimension in good water governance (Hoekstra, 2011).

The WF and CF concepts have similarities; however, their roots and intended purposes differ. The CF was formulated to quantify the contribution of various activities to climate change. The history of the WF lies in the exploration of water use along supply chains and in the search for a tool to understand the global dimension of water as a natural resource. Although each footprint has different roots and characteristics and addresses different research and policy questions, there is a tendency among practitioners in the fields of environmental policy and corporate social responsibility to treat the WF in a similar way as the CF. For example, popular terms such as 'carbon neutral' and 'carbon offsetting' are immediately adapted to 'water neutral' and 'water offsetting' without any particular attention to the appropriateness and applicability of these ideas for water. Similarly, initiatives are taken to develop water labels for products in analogy to carbon labels and to incorporate the WF into Life Cycle Assessment (LCA) for products in the same way as was done with the CF. Most notably, people have a tendency to interpret the numbers of the WF without considering their spatial and temporal characteristics as is commonly done in CF analysis. Each footprint needs to be seen within its appropriate context and interpreted with care as it is built around different research questions and tells a different story.

The objective of this study is to analyse the origins and the characteristics of the carbon and water footprints in order to understand their similarities and differences and to derive lessons on how society and business can adequately build on the two concepts. We compare the two concepts from a methodological point of view and discuss response mechanisms that have been developed, with the hope that experiences in one field might be able to benefit the other.

6.2 Origins of the carbon and water footprint concepts

The carbon and water footprint concepts were introduced about a decade ago, simultaneously, but independently from one another. The CF arose out of the debate on climate change, as a tool to measure GHG emissions. The WF was introduced in the field of water resources management, as a tool to measure water use in relation to consumption patterns. In both cases, the terminology chosen was inspired by the ecological footprint (EF), which had been introduced in the 1990s (Rees, 1992). All footprints measure, in different ways, human appropriation of the planet's natural resources and carrying capacity (Galli et al., 2012; Giljum et al., 2011; Hoekstra, 2009) (Figure 6.1). The EF measures the use of bioproductive space in hectares; the WF measures the consumption and contamination of freshwater resources in cubic metres per year; and the CF measures the emission of gases that contribute to heating the planet in carbon dioxide (CO_2)-equivalents per unit of time or product. A common property of all footprints is that they can be related to specific activities, products and consumption patterns. Recently, the nitrogen footprint was introduced as a tool to measure the amount of nitrogen released into the environment in relation to consumption (Leach et al., 2012). In this report, we focus on the CF and WF.

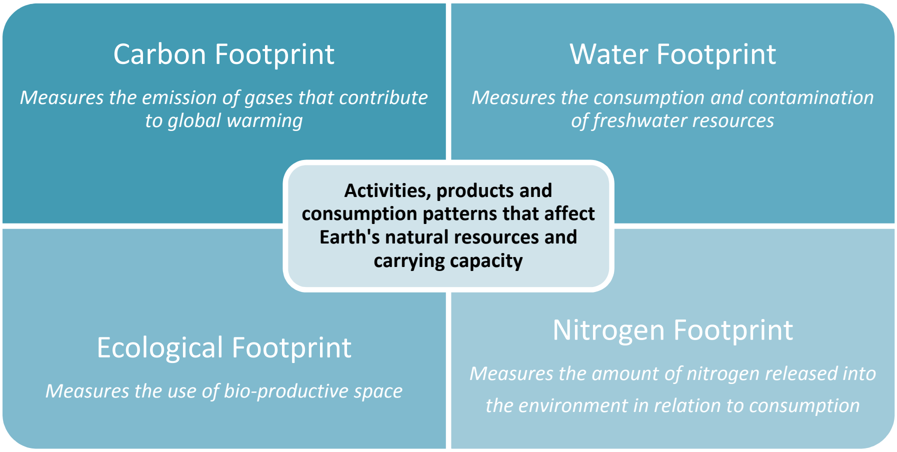

Figure 6.1. Footprint concepts

6.2.1 The carbon footprint

Concern about climate change started with the scientific recognition of the relationship between CO_2 emissions and global warming. The increasing worldwide interest in the causes and consequences of climate change, and in exploring ways to respond, resulted in the formation of the Intergovernmental Panel on Climate Change (IPCC) in 1988. The IPCC was the first worldwide effort to create awareness of global warming and to feed scientific insights on climate change to governments. The IPCC released its first assessment report in 1990 (Houghton et al., 1990). This report played an important role in the establishment of the United Nations Framework Convention on Climate Change (UNFCCC), an international environmental treaty with the goal of stabilizing GHG concentrations in the atmosphere at a level that prevents dangerous anthropogenic interference with the climate system. Efforts under the UNFCCC led to the Kyoto Protocol (UN, 1998), an international agreement to cut GHG emissions, with specific reduction targets by country, signed in December 1997 and entered into force in 2005. The overall goal was a collective reduction of GHG emissions by 5.2% in 2012 compared to the emission levels of 1990.

To achieve its goal, the Kyoto Protocol installed a system for emissions trading and some mechanisms to allow for offsetting GHG emissions. The system of emissions trading (the ‘carbon market’) allows countries to sell unused emission permits to countries that are over their targets. In addition to trade in emission permits (so-called assigned amount units [AAUs]), the Kyoto Protocol also allows trade in credits that can be obtained through various offsetting mechanisms:

1. Clean Development Mechanism (CDM): an industrialized country with an emission-reduction or emission-limitation commitment can implement emission-reduction projects in developing countries. In this way, the country earns saleable certified emission reduction credits (CERs).
2. Joint Implementation (JI): an industrialized or in-transition country with an emission-reduction or emission-limitation commitment can earn emission reduction units (ERUs) from an emission-reduction or emission-removal project in another industrialized country or a country in transition.
3. A mechanism that allows countries to earn removal units (RMUs) through projects that sequester CO_2, such as reforestation.

CERs, ERUs and RMUs are all expressed in CO_2 equivalents and can all be traded on the carbon market and counted by a country towards meeting its Kyoto target. Parallel to the formal carbon market under the Kyoto Protocol, in which companies, governments and other entities buy emission rights or carbon offsets to comply with caps on the total amount of CO_2 they are allowed to emit, another, voluntary carbon market has grown, in which individuals, companies and governments purchase carbon offsets to voluntarily mitigate their GHG emissions. The CF is increasingly used as the stick by which to measure the volume of GHG emissions related to specific activities or products.

The CF can be seen as an offspring of the EF concept, which was developed by Wackernagel and Rees (1996). The EF, expressed in hectares, includes a component that represents the area required to sequester enough carbon emissions to avoid an increase in atmospheric CO_2 (Wackernagel et al., 2002). In this sense, the EF ‘includes’ a carbon footprint (expressed in hectares). However, the focus on land requirement in the EF is not very helpful if the interest is not so much in land requirement but more directly in the volume of CO_2 and other GHG emissions. Thus, in response to the interest of governments and companies in GHG emissions and global warming, the CF has become a modified, independent concept, expressed in terms of emitted CO_2 equivalents (East, 2008; Moss et al., 2008). It is not clear when and by whom the term CF was used for the first time, but it is found in newspaper articles as early as the year 2000 (Biddle, 2000; Sorensen, 2000). According to Safire (2008), it was an enormous BP media campaign in 2005 that gave a big boost to wider use of the concept. By then, we can also see the term being using in the scientific literature (e.g. Haefeli and Telnes, 2005). In the library of publications in the *Web of Science*, the CF is mentioned for the first time in January 2007, in a letter to *Nature* (Hammond, 2007).

Despite its popularity and use in commerce, there is no universally accepted definition of CF. Today it describes the narrowest to the widest interpretation of GHG emission measurement (East, 2008; Finkbeiner, 2009; Pandey et al., 2011; Peters, 2010; Wiedmann and Minx, 2007). Although the Kyoto Protocol does not use the term (the Protocol was conceived long before the CF), it would make some sense to be able to take this formal international agreement as a reference for the definition of the CF, because measuring GHG emissions is at the core of the Protocol. However, the Kyoto Protocol is primarily a political construct, not a scientific effort to define in a comprehensive and systematic manner how to quantify direct and indirect GHG emissions in relation to activities, products and consumption patterns (e.g. it has openings to discount certain emissions that intuitively should be counted).

The CF concept has been defined mainly by private organizations and businesses (Kleiner, 2007; Wiedmann and Minx, 2007). The scientific community jumped on the train in 2007, after the concept had already started to spread in business and commerce. The most extensive survey on the definition of the CF was done by Wiedmann and Minx (2007). Their research shows that the available studies do not offer uniformity in the definitions and methodology of the CF. They suggest the definition of CF is ‘a measure of the exclusive total amount of CO_2 emissions that is directly and indirectly caused by an activity or is accumulated over the life stages of a product'. Pandey et al. (2011) describe the CF as 'the quantity of GHGs expressed in terms of CO_2-equivalent, emitted into the atmosphere by an individual, organization, process, product, or event from within a specified boundary'. In both cases, the definition does not allow for subtractions as a result of offsetting. In practice, however, companies tend to claim that carbon offsetting reduces their CF. Furthermore, in practice it is not always clear whether CFs communicated refer only to direct GHG emissions or indirect ones as well – scientists generally define the CF of a product as including both direct and indirect emissions. Both in science and in practice, the term is applied to different entities: single processes, whole supply chains (or all life-cycle stages) of products, individual consumers, populations, companies, industry sectors, and all sorts of activities and organizations.

6.2.2 The water footprint

The WF concept is primarily rooted in the desire to illustrate the hidden links between human consumption and water use and between global trade and water resources management (Hoekstra and Chapagain, 2007, 2008). The WF was developed as an analogy to the EF concept. It was first introduced by Hoekstra in 2002 to provide a consumption-based indicator of water use (Hoekstra, 2003). It is an indicator of freshwater use that shows direct *and indirect* water use of a producer or consumer. The first assessment of national WFs was carried out by Hoekstra and Hung (2002). A more extended assessment was done by Hoekstra and Chapagain (2007, 2008) and a third, even more detailed, assessment was done by Hoekstra and Mekonnen (2012*a*).

Unlike the CF, which emerged in practice, the WF was born in science. The WF started to gain broad interest from about 2008, the year in which the Water Footprint Network (WFN) was established – a network of academic institutions, governments, non-governmental organizations, companies, investors and UN institutions. One of the aims of the Network is to ensure the establishment of one common language and a coherent and scientifically sound framework for Water Footprint Assessment (WFA) that serves different interests; for example, WFA for products and companies, but also national WFA.

In 2009, about seven years after the first use of the WF concept, the WFN published the first version of the global standard for WFA. Two years later the second version was published (Hoekstra et al., 2011). This standard, which was produced in a process of consultations with organizations and researchers worldwide and subjected to scientific peer review, has comprehensive definitions and methods for WF accounting. It shows how WFs are calculated for individual processes and products, as well as for consumers, nations and businesses.

It also includes methods for WF sustainability assessment and a list of WF response options. As could be expected, the definitions and methods have been challenged (Wichelns, 2011), but no alternative methodological framework has been developed (unlike in the case of the CF). The WFN standard contains definitions of the WF, of process steps, products, producers and consumers, as well as of the WF within a geographically delineated area. The WF is, in general, an indicator of freshwater appropriation, measured in terms of water volumes consumed (evaporated or incorporated into a product) and polluted per unit of time. The WF concept is further defined more specifically for a particular process or product, and for any well-defined group of consumers (e.g. individual, family, village, city, province, state, nation) or producers (e.g. public organization, private enterprise, economic sector). From a producer and consumer perspective, the WF is an indicator of both their direct and their indirect water use. The WF is a geographically and temporally explicit indicator, showing not only volumes of water use and pollution, but also their locations.

6.3 Comparison of the carbon and water footprints from a methodological viewpoint

The carbon and water footprint concepts complement each other, addressing different environmental issues: climate change and freshwater scarcity. Although there are similarities in the way both footprints are defined and calculated, they differ in important ways as well (Table 6.1). The location and timing within the year of GHG emissions, for example, are not relevant, whereas location and timing of water consumption and pollution matter critically. It is important to understand the similarities and differences between the two footprints for formulation of wise policy responses. This understanding can help decision-makers recognize to what extent the type of mitigation policies that have been formulated for one footprint can be applied to the other.

6.3.1 Environmental pressure indicators

Both the CF and the WF are 'pressure indicators' (Rotmans and De Vries, 1997; UNEP, 2012). Environmental pressure indicators measure the human use of natural resources and the anthropogenic emission of compounds into the environment, but they do not show the resulting change in the environment. The CF, for instance, shows GHG emissions, not the resultant higher GHG concentrations in the atmosphere or the subsequent changes in temperature, evaporation, precipitation or sea level. The WF shows the human consumption and contamination of freshwater resources, not the resultant changes in runoff and water quality in rivers and aquifers. As pressure indicators, the CF and WF show neither resultant environmental changes nor final impacts of those environmental changes on human beings (e.g. health) and ecosystems (e.g. biodiversity), but they are still useful measures of pressure that humans put on the environment for policy-makers working to address overexploitation of natural resources and the planet's carrying capacity. Reduction strategies concerning CF and WF fit within policy aimed to mitigate the causes of environmental change and subsequent societal and ecological impacts. CF reduction, for example, fits within a policy of climate change mitigation. For climate change *adaptation*, other measures and indicators would need to be used. Similarly, WF reduction suits a policy to lessen water scarcity and water quality deterioration. For *coping* with increased water scarcity and contaminated water, other measures and indicators are better suited.

Table 6.1. Comparison of carbon and water footprints.

	Carbon footprint (CF)	Water footprint (WF)
What is measured	The anthropogenic emission of greenhouse gases (GHG).	The human appropriation of freshwater resources in terms of volumes of water consumed and polluted.
Unit of measurement	Mass of carbon dioxide (CO_2)-equivalents per unit of time or per unit of product.	Water volume per unit of time or per unit of product.
Spatiotemporal dimension	Timing within the year and place of emissions are not specified. It does not matter where and when carbon emissions occur; carbon emission units are interchangeable.	WFs are specified in time and by location. It matters where and when a WF occurs; WF units are not interchangeable. For some uses, total/average WFs are shown, thus leaving out spatiotemporal specifications.
Footprint components	CF per type of GHG: CO_2, CH_4, N_2O, HFC, PFC, and SF_6. Emissions per type of gas are weighted by their global warming potential before adding.	Blue, green and grey WF. If added, the three components are added without weighting.
Entities for which the footprint can be calculated	Processes, products, companies, industry sectors, individual consumers, groups of consumers, geographically delineated areas.	Processes, products, companies, industry sectors, individual consumers, groups of consumers, geographically delineated areas.
Calculation methods	Bottom-up approach: - For processes, products and small entities - The method of Life Cycle Assessment (LCA) Top-down approach: - For sector, national and global studies - The method of Environmentally Extended Input-Output Analysis (EE-IOA) Hybrid approach: LCA and EE-IOA for products, nations, organizations	Bottom-up approach: - For processes, products and businesses, but also for sector, national and global studies - The method of bottom-up accounting in Water Footprint Assessment (WFA) - For products, the accounting along supply chains in WFA is similar to the accounting in the Life Cycle Inventory stage of LCA studies Top-down approach: - For sector, national and global studies - The method of top-down accounting in WFA, which is based on drawing national virtual water trade balances - The method of EE-IOA is used as an alternative
Scope	1. Direct emissions 2. Indirect emissions from electricity used 3. Other indirect emissions	Always includes direct and indirect WF.
Sustainability of the footprint	Additional information is required to assess the sustainability of the CF. For the planet as a whole, a maximum allowable GHG concentration needs to be estimated, which needs to be translated to a CF cap. For specific processes and products, CF benchmarks can be used.	Additional information is required to assess the sustainability of the WF. Per catchment area, freshwater availability and waste assimilation capacity need to be estimated, which form a WF cap for the catchment. For specific processes and products, WF benchmarks can be used.

6.3.2 Units of measurement

The CF is expressed in mass units (e.g. kg or tonnes) per unit of time (generally per year). The CF of a product is expressed in mass units per unit of product. In cases in which only CO_2 is included in the calculation, the unit is kg CO_2; if other GHGs are included, the unit is kg CO_2-equivalents (CO_2-e). CO_2-equivalents are calculated by multiplying the various GHG emissions by their 100-year global warming potential. In most cases, the six GHGs identified by the Kyoto Protocol are included in the analysis: CO_2, CH_4, N_2O, HFC, PFC and SF_6. However, there is no common understanding and agreement of which gases should be included in CF studies (East, 2008; Kleiner, 2007). The selection of gases depends on the standard followed and the scope and type of the CF study. Although some studies suggest to include only CO_2 (Wiedmann and Minx, 2007), the common understanding and direction in CF calculations is to include all six Kyoto Protocol gases (Pandey et al., 2011; Peters, 2010).

The WF is measured in terms of water volume (e.g. L or m^3) per unit of time (e.g. day, month, year). A product WF is expressed as a water volume per unit of product. The amount of product can be measured in various ways; for example, in terms of mass, volume, number of pieces, monetary value or energy content. Mekonnen and Hoekstra (2012) quantify and compare, for instance, the water footprint of various crop and animal products in terms of L per kg, L per kcal, L per g of protein, and L per g of fat content.

6.3.3 Spatial and temporal dimensions

When determining CFs, GHG emissions are usually estimated with the help of emission factors. Emission factors are available for a wide range of processes (WRI and WBCSD, 2004). Most CF studies are based on global average data on emissions per unit of good or service. However, national emission factors have also been introduced to reflect divergent local characteristics (Solomon et al., 2007). WFs provide spatiotemporally explicit information on how water is appropriated for various human purposes. In WF accounting, the approach is to use local productivities (Mekonnen and Hoekstra, 2011b, 2012). Obviously, at the global level it does not matter whether footprint analysis is carried out on the basis of local or global average productivities, because adding the results obtained with local data will yield the same global result as an analysis based on global average data. But on a national level, the result will differ when local productivities are used instead of global averages.

It does not matter where and when carbon emissions occur; carbon emission units are therefore interchangeable. This is fundamentally different for the WF: it matters where and when a WF occurs. WF units are therefore not interchangeable. This is particularly relevant in the discussion about offsetting. For example, the WF in one catchment cannot be compensated for by offsetting activities to reduce the WF in another catchment.

6.3.4 Footprint components

The CF comprises as many components as GHGs that have been included in the analysis. The emissions per type of gas are weighted by their global warming potential. In contrast, the WF always consists of three components:

- **Blue WF:** The consumption of ‘blue’ water resources (surface water and groundwater).
- **Green WF:** The consumption of ‘green’ water resources (rainwater stored in the soil as soil moisture).
- **Grey WF:** This refers to pollution and is defined as the volume of freshwater that is required to assimilate the load of pollutants based on existing ambient water quality standards (Hoekstra et al., 2011).

‘Consumption’ refers to the loss of water from the available ground–surface water body in a catchment area, which happens when water evaporates, is incorporated into a product, or is transported to another catchment area or the sea.

The WF is often presented as one aggregate number; in that case, the three WF components are added without weighting. It has been recognized that although this approach may be sufficient for awareness raising, for the purpose of policy formulation it is essential to clearly distinguish the three WF components. In its definitive form, the WF is a multidimensional indicator of water use, explicitly showing water consumption (green and blue WF) and pollution (grey WF) as a function of space and time.

Some researchers from the LCA community have proposed adding WF components after multiplying each with a local weighting factor to account for differences in local impact, thus obtaining 'litres water-equivalent' (Pfister and Hellweg, 2009; Ridoutt and Pfister, 2010*a*; Ridoutt et al., 2009). By taking blue water scarcity in a catchment as the weighting factor, a blue WF in a water-abundant catchment would count less than a similar blue WF in a water-scarce area. This idea of weighting was undoubtedly inspired by the weighting of different GHGs in CF calculations, but this approach is based on a misunderstanding of the water scarcity issue. The WF does not aim to reveal the local hydrological impact of water consumption; it aims to measure the use of freshwater resources, which is helpful in determining how to allocate water among competing demands. One litre of water used does not become more or less than one litre according to the degree of water scarcity in a catchment. Weighting the WF in two locations based on local water scarcity is like weighting oil consumption in two locations based on the scarcity of local oil reserves – it does not make sense (Hoekstra et al., 2011). Furthermore, if the WF of a product or company were to be calculated by multiplying consumed volumes by local water scarcity, another problem arises: because water scarcity in a catchment is defined as the total WF in the catchment divided by the water availability, the WF of a product produced in a certain catchment would increase (or decrease) if *other users* in that catchment increased (or decreased) their WF. This way of measurement is counterintuitive (i.e. how can you explain that 'my WF depends on your WF') and does not offer a proper incentive for companies to reduce their WF – if companies would reduce *their* WF, they would reduce the WF of others as well. Unfortunately, the idea of weighting water volumes based on local water scarcity seems to be rather persistent in the LCA community (Berger and Finkbeiner, 2010). The confusion is that some researchers in that community treat the WF as an environmental impact indicator, while in fact it is an environmental pressure indicator, measuring the intensity of resource use.

6.3.5 Entities for which the footprints can be calculated

The CF and WF are similar in that the concepts can be applied to a wide variety of entities. In both cases, the basic building block is the footprint of a process. Based on the CF or WF of a process, the CF or WF of a product can be calculated by summing the CFs or WFs over the steps of its supply chain or life cycle. By summing the CFs or WFs of the products produced or consumed, the CF or WF of a company, an industrial sector, an individual consumer, or a group of consumers can be assessed. The total CF or WF occurring within a certain geographically delineated area (e.g. the territory of a country) is obtained by summing the CFs or WFs of the activities within that area. The WF concept has been applied to assess the WF of national consumption from its inception on (Hoekstra and Hung, 2002), while the CF concept originally was applied to products and has only more recently been applied to national consumption (Hertwich and Peters, 2009).

6.3.6 Calculation methods

Although the CF is widely used as a yardstick, there is little uniformity in its calculation methods. The main differences are in:

- the scope of the study (indirect emissions are often excluded)
- the gases included
- the weighting of these gases to arrive at CO_2-equivalents
- the system boundaries chosen to determine how to truncate the analysis of emissions in the supply chain

There is also no unanimity on whether offsetting is valid as a way to reduce CF, and if so, how certain offsetting activities can be counted.

Alternative calculation methods and standards have been formulated by different organizations (Kenny and Gray, 2009; Padgett et al., 2008; Pandey et al., 2011; Wiedmann and Minx, 2007). At the product level, CF standardization has been under discussion and several organizations have published their own guidelines and standards. The *Publicly Available Specifications 2050* of the British Standards Institution was one of the first standards describing calculation methods for product CFs – they were first published in

2008 and updated three years later (BSI, 2011). This standard describes the calculation of GHG emissions of goods and services based on the LCA approach. Other standards in wide use are the *GHG Protocol* of the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD) (2004) and their recently published *Product Life Cycle Accounting and Reporting Standard* (2011). The International Organization for Standardization (ISO) is currently developing a product CF standard known as ISO 14067 (ISO, 2012*a*). Other ISO standards related to the CF are ISO 14040 on Life Cycle Assessment (ISO, 2006*a*) and ISO 14064 on Greenhouse Gases (ISO, 2006*b*). The Japanese Industrial Standards Committee published a *Basic Guideline of the Carbon Footprint of Products* (JISC, 2009).

The three main approaches used to calculate CFs are the bottom-up, top-down and hybrid approaches (Matthews et al., 2008; Peters, 2010; Wiedmann and Minx, 2007). The bottom-up approach is based on LCA, a method that estimates the environmental impact of products by ‘cradle to grave’ analysis. This method is mainly used for estimation of the CF of products and small entities (Finkbeiner, 2009; Peters, 2010; Schmidt, 2009; SETAC, 2008; Sinden, 2009; Weidema et al., 2008). There are numerous examples of this method being applied to the CF calculation of specific products: computers (O'Connell and Stutz, 2010), newspapers and magazines (Boguski, 2010), and animal products (Edwards-Jones et al., 2009; Flysjö et al., 2011). Although the bottom-up approach produces results with a relatively high level of precision, it is data-demanding and brings system boundary and truncation problems (Wiedmann, 2009b).

The top-down approach is used for calculating the CF of large entities such as sectors, countries and regions. Environmentally Extended Input-Output Analysis (EE-IOA) is the main method for top-down calculations (Minx et al., 2009; Pandey et al., 2011; Wiedmann, 2009b). Such analysis makes use of an economic input-output model, which represents the interdependencies between different sectors and final consumption in the national economy or between the sectors in different national economies. An input-output model contains a matrix that shows how the output of one industry is an input to another. It also includes imports and exports and final consumption. Inputs and outputs are expressed in monetary terms: the model shows the value of economic transactions between different sectors in an economy. A monetary input-output model can be extended with environment-related information for each sector, such as its emissions and natural resource use, thus allowing for EE-IOA. At the national level, EE-IOA is based only on national input and output tables, which can bring significant errors into CF analysis (Minx et al., 2009). The introduction of multi-regional input-output models has solved this problem. However, two major challenges remain: (i) the relatively coarse schematization of the economy in input-output models (whereby economic activities with rather different natural resource use and emission intensities are part of one sector) and (ii) the approximation of (often unknown) physical flows between sectors by the (known) inter-sector monetary flows (which ignores the fact that traded goods and services between sectors are not homogeneous). National CF studies based on EE-IOA have been carried out, for example, for the United Kingdom (Druckman and Jackson, 2009; Wiedmann et al., 2010), Australia (Wood and Dey, 2009), Japan (Nansai et al., 2009), Brazil (Machado et al., 2001), the United States of America (Weber and Matthews, 2008) and China (Chen and Chen, 2010; Zhao et al., 2009). Global assessments of national CFs have been carried out by Hertwich and Peters (2009) and Wilting and Vringer (2009).

The hybrid approach to CF accounting combines the specificity of process analysis (using LCA) with the system completeness of EE-IOA (Lenzen and Crawford, 2009). This approach retains the detail and accuracy of the bottom-up approach (which is especially relevant in carbon-intensive sectors). In the hybrid approach, first- and second-order process data are collected for the product or service and higher order requirements are covered by input-output analysis (Wiedmann and Minx, 2007).

In WF accounting, there is only one standard: the *Global Water Footprint Standard* published by the WFN in 2009 and revised in 2011 (Hoekstra et al., 2011). This standard covers comprehensive definitions and methods for WFA. WFA has four stages: (i) setting goals and scope; (ii) accounting; (iii) assessing sustainability; and (iv) formulating responses. The standard covers methods for the calculation of the WF of processes, products, companies, consumers, and consumer groups (e.g. people of a nation), and also includes guidelines for sustainability assessment and response formulation. The WFs of single process steps form the basic building blocks of all WF accounts. The WF of a product, for example, is the aggregate of the WFs of the relevant process steps. The WF within a geographically delineated area is equal to the sum of the WFs of all processes taking place within that area (Hoekstra et al., 2011). According to the standard, offsetting activities cannot be counted as WF reduction. Furthermore, the term WF can be used only to refer to the sum of direct and indirect WFs, so that no confusion can arise as to the scope of the term. Companies can refer to their *direct (operational) WF*, which excludes their *indirect (supply-chain) WF*.

The ISO has taken the initiative, under its Technical Committee on Life Cycle Assessment, to develop a standard related to the WF: ISO 14046 (ISO, 2012*b*). By its position under the LCA committee, the scope will be limited to processes and products and align to the LCA methodology as formulated in other ISO standards in the LCA field. By focussing on procedural issues rather than calculation methods, the standard will probably (and hopefully) not be in conflict with the *Global Water Footprint Standard* published by the WFN.

There are two approaches for WFA: bottom-up and top-down (Hoekstra et al., 2011). No hybrid approach has been developed, although recently there has been an initiative in this direction (Ewing et al., 2012). The bottom-up approach can be used for all sorts of WF accounts. When calculating the WF of products with the bottom-up approach, the accounting over supply chains is done in the same way as in a Life Cycle Inventory in LCA studies. There are product WF studies based on the bottom-up approach for a large variety of crop products (Mekonnen and Hoekstra, 2011b) and farm animal products (Mekonnen and Hoekstra, 2012). More specific product studies have been carried out for cotton (Chapagain et al., 2006), coffee and tea (Chapagain and Hoekstra, 2007; Jefferies et al., 2012), biofuels (Gerbens-Leenes et al., 2009b), pizza and pasta (Aldaya and Hoekstra, 2010), wheat (Mekonnen and Hoekstra, 2010c), soft drinks (Ercin et al., 2011), rice (Chapagain and Hoekstra, 2011), soy products (Ercin et al., 2012*a*) and margarine (Jefferies et al., 2012). The bottom-up approach can also be applied for the calculation of the WF of companies, sectors, nations and regions. The WF of the consumers in a country, for example, can be calculated by multiplying all the goods and services consumed by the inhabitants of the country by the respective water needs for those goods and services (Hoekstra and Mekonnen, 2012*a*).

The bottom-up approach is generic and precise and can be applied for all WF calculations. However, it can be data-demanding, especially for large entities (as with the CF bottom-up approach). For the calculation of the WF of sectors, provinces, nations and regions, the top-down approach can be used as an alternative. This approach is based on input data on WF per entity (e.g. sector, province, nation, river basin) and virtual water flows between these entities. The classic way in which the top-down approach has been applied is based on drawing virtual water balances of countries using trade data and data on WFs of traded commodities (Hoekstra and Chapagain, 2007, 2008). Alternatively, the EE-IOA is nowadays also applied for WF studies (Ewing et al., 2012).

In the classic top-down approach, the WF of the people living in a province, nation or river basin is calculated as the total use of water resources in the area under consideration *plus* the gross virtual water import into the area *minus* the gross virtual water export. Virtual water import is the volume of water used in other countries to make goods and services imported to and consumed within the country considered. Virtual water export is the volume of water used domestically for making export products which are consumed elsewhere (Hoekstra and Chapagain, 2007, 2008). The bottom-up and top-down calculations theoretically result in the same figure, provided there is no product stock change over a year. The advantage of the bottom-up approach is its precision. However, as noted, it is data-intensive and depends on the quality of consumption data. The top-down approach does not require consumption data, but it does require trade data and is therefore vulnerable to the quality of that data (Van Oel et al., 2009). The top-down approach was used in all of the early national WF studies, but recent studies tend to use the bottom-up approach (Hoekstra and Mekonnen, 2012*a*; Ercin et al., 2012*b*).

Input-output modelling has been used as an alternative tool for top-down WF calculations for sectors and nations (Daniels et al., 2011; Duarte and Yang, 2011). It has been used mainly for national WF studies – China (Guan and Hubacek, 2007; Hubacek et al., 2009; Zhang et al., 2011*b*; Zhao et al., 2009), Japan (Horie et al., 2011), Spain

(Cazcarro et al., 2011) and Mexico (López-Morales and Duchin, 2011) – but also for areas and cities – Andalusia (Velázquez, 2006; Dietzenbacher and Velázquez, 2007), Beijing (Zhang et al., 2011*a*), Zhangye City (Wang et al., 2009) and for the Yellow River Basin (Feng et al., 2012). A global study with a multi-regional input-output model was done by Feng et al. (2011), who compared the top-down approach with bottom-up techniques.

6.3.7 Scope

For corporate CF accounting, three scopes have been defined (WRI and WBCSD, 2004):

- Scope 1 refers to the accounting of *direct* GHG emissions, which occur from sources that are owned or controlled by the company (e.g. the emissions from combustion in owned or controlled boilers, furnaces, vehicles).
- Scope 2 refers to accounting of *indirect* GHG emissions from the generation of purchased electricity used by the company.
- Scope 3 refers to other indirect GHG emissions, which are a consequence of the activities of the company, but occur from sources not owned or controlled by it (e.g. extraction and production of purchased materials, transportation of purchased fuels) (Matthews et al., 2008).

The distinction between direct and indirect is also made in WF accounting. The total WF of a consumer or producer refers, by definition, to the sum of the direct (operational) and indirect (supply-chain) WFs of the consumer or producer. Without specification, the term WF refers to the sum of direct and indirect WFs. The distinction between scopes 2 and 3 as applied in CF accounting is not useful in WF accounting.

6.3.8 Sustainability of the carbon and water footprints

As indicators of pressure on the planet, the CF and WF by themselves tell little about impact. They need to be compared with the planet's carrying capacity. The global CF needs to be seen relative to the maximum sustainable global CF (the 'carbon cap'), which depends on the amount of GHGs that can be assimilated without causing more than a certain maximum degree of global warming (Solomon et al., 2007). The sustainability of the WF needs to be evaluated per river basin: the WF in a catchment needs to be seen relative to the maximum sustainable WF in the area. This explains why it is relevant to know where the WF is located. The maximum sustainable WF in a catchment depends on the runoff and environmental flow requirements in the area (Hoekstra et al., 2011, 2012; Ridoutt and Pfister, 2010*b*). The global maximum sustainable WF is equal to the sum of the local maximum sustainable WFs. In order to have a more practical guide for assessing sustainability at the level of individual processes and products, process- and product-specific benchmarks for CF and WF can be developed (Groenenberg and Blok, 2002; Zwart et al., 2010).

6.4 Comparison of responses to the carbon and water footprints

In response to the increasing concern about climate change, governments, businesses and consumers are considering ways to decrease the CF of activities and products. The two main response strategies are reduction and offsetting. *Reduction* refers to doing things in a less carbon intensive way – achieved through increasing carbon efficiency by applying low-carbon technology, which has less GHG emission per unit of production – or ceasing certain activities of production or consumption altogether. *Offsetting* refers to taking external actions to compensate for a certain CF by means of some form of carbon capture or reduction elsewhere by others. If the CF of a certain activity is offset 100%, it is sometimes claimed that the activity is 'carbon neutral'. The concepts of carbon offsetting and neutrality are applied and supported widely by business, government and individual consumers (Kollmuss et al., 2008; Moss et al., 2008; Murray and Dey, 2009).

Whereas various CF reduction and offsetting mechanisms have already been developed and implemented, WF response mechanisms are still being explored. The broad public interest in the WF is more recent than the interest in the CF. It is not surprising that the same types of policy response that have been developed for the CF are now proposed for the WF, and there are many analogous terms in the two fields: CF reduction vs WF reduction; carbon efficiency vs water efficiency; carbon offsetting vs water offsetting; carbon neutral vs water neutral; carbon cap vs water footprint cap; carbon permits vs water footprint permits; and carbon labelling vs water labelling. All of these concepts are new in the field of water resources management except for 'water efficiency', which has been applied for decades – but even this takes on a new dimension: whereas it generally referred to water productivity at field level or within a factory, a supply-chain perspective is now added.

Cross-fertilization occurs when insights and concepts from the sphere of climate change mitigation are translated to the sphere of water. This can be fruitful, but also bears risks. Water is not the same as carbon, so it should be questioned whether solutions for carbon can be copied for water. Furthermore, not all 'solutions' that have been developed for carbon appear to be effective, so they should be critically evaluated before being applied elsewhere. Hoekstra (2008) notes that, undoubtedly, there will be a great market for water offsetting and water neutrality, comparable to the market for carbon offsetting and neutrality, but the extent to which this market will become effective in contributing to a more efficient, sustainable and equitable use of the globe's water resources will depend on the rules of the market. Without agreed definitions and guidelines on what counts as water offsetting and neutrality, the terms are most likely to end up as catchwords for raising funds for charity projects in the water sector rather than as effective means to achieve measurable overall WF reductions.

6.4.1 The need for reduction: Maximum sustainable footprint levels

There is a general acknowledgment that humanity's CF and WF have surpassed sustainable levels and that society must make efforts to reduce them, but it appears to be quite difficult to establish unambiguous and agreed upon maximum sustainable levels for these footprints. Knowing their ceilings is instrumental in formulating reduction strategies. The maximum sustainable level for the global anthropogenic CF depends on the maximum allowable global temperature increase, which in turn depends on the societal and ecological impacts that are expected at different degrees of global warming. At the United Nations Climate Change Conference in Copenhagen in 2009, note was taken of the scientific view that the increase in global temperature should be below two degrees Celsius. If governments would sign up to such a target – which they did not do – there would be a basis for establishing a maximum concentration of GHGs in the atmosphere, and then a maximum CF in order to remain below this maximum concentration. This in itself is not an easy task. The challenge has long been framed as one of stabilizing GHG concentrations at particular levels, such as 550, 450 or even 350 parts per million (p.p.m.) CO_2-equivalents.

Recently, several researchers have proposed an alternative view, in which the mitigation challenge is framed as that of putting a cap on total cumulative GHG emissions since the start of the industrial revolution (Allen et al., 2009; Matthews et al., 2009). This proposal is built on the insight that the total allowable emissions for climate stabilization do not depend on the timing of those emissions. It has been estimated that the peak warming above pre-industrial temperatures would be limited to two degrees Celsius with a 50% probability of success if cumulative CO_2 emissions are capped at 1000 trillion tonnes of carbon, more than half of which already has been emitted (Allen et al., 2009; Raupach, 2009). From this perspective, the maximum sustainable CF cannot be formulated as a certain ceiling to the annual CF, but should be seen as a maximum budget we can spend between today and, say, the end of this century – which means that the maximum CF should continually decline and ultimately reach zero.

But even before this new insight on the required cap to humanity's CF, there was already broad scientific consensus that anthropogenic GHG emissions are currently far beyond the level required to achieve a maximum of two degrees Celsius global warming (Solomon et al., 2007). Although the commitments made by governments in the Kyoto Protocol to reduce national GHG emissions by certain percentages are not nearly sufficient in the view of a two-degree target, the *idea* of setting a cap to GHG emissions has been institutionalized, which is probably the biggest achievement of the Protocol. Future focus should be on sticking to that idea and further negotiating the level of national caps (and even reducing caps over time), and on the mechanisms to be installed to ensure that caps are not exceeded.

In contrast, even the idea of a maximum sustainable WF has not yet been politically debated. As in the case of the CF, it is not easy to define what the maximum sustainable WF of humanity is – and for the WF, another level of complexity is that the maximum sustainable global WF is the sum of the maximum sustainable WFs in all the river basins of the world. Furthermore, timing within the year is a factor. As shown by

Hoekstra et al. (2012), unsustainable WFs become manifest during certain periods of the year (generally when water availability is relatively low while the WF is relatively large), so maximum sustainable WFs have to be established per catchment on a monthly rather than an annual basis. Little research has been done on assessing the maximum sustainable global WF. Ridoutt and Pfister (2010*b*) argue that the global WF must be reduced by about half to reach a sustainable level of water utilization and they consider such a target realistic given the potential for water productivity improvements in agriculture and industry and the steps that could be taken to limit food chain waste.

A question often posed in the context of WF reduction is whether it is relevant to reduce WFs in water-abundant river basins (e.g. Wichelns, 2011; Ridoutt and Huang, 2012). Reducing the aggregate WF in the most water-scarce catchments deserves priority indeed, but this requires global action. As argued by Hoekstra and Mekonnen (2012*b*), an important component of the solution to overexploitation of blue freshwater resources in water-stressed catchments is to increase water productivities (reduce product WFs) in water-abundant areas. Because water-intensive commodities can be traded internationally, wise allocation of freshwater resources to alternative purposes is a question with a global dimension (Hoekstra, 2011). Water-abundant areas often show low water productivities (tonnes per m^3) and thus large product WFs (m^3 per tonne). Even though the local environmental impacts of water use in these areas can be small, it would be a mistake to leave them out of the scope of water policy.

6.4.2 Reduction of footprints by increasing carbon and water efficiency

Carbon efficiency is a popular term referring to the CF per unit of Gross Domestic Product (GDP) in an economy, or more specifically to the CF of specific sectors or activities, always per unit of production. A related term is energy efficiency. Companies and governments usually translate the need for CF reduction into a need to increase energy efficiency in industry, transportation and households, assuming that decreased energy use per unit of good or service produced automatically translates into reduced GHG emissions. There is also the recognition that we need to shift from carbon-intensive forms of energy like coal and oil to less carbon-intensive forms like gas or, even better, renewable forms of energy like wind, solar, hydro or bioenergy.

Although the strategies of increasing energy efficiency and shifting to renewables seem quite straightforward, they are not always as effective in reducing GHG emissions as we would expect. In practice, increasing energy efficiency does not necessarily correlate to an overall reduction in energy use. More efficient production means that the same can be produced with less energy, but it also means that more can be produced with the same energy. Increased energy efficiency may thus contribute to increasing levels of production and consumption. This is called the 'rebound effect', which describes increases in resource or energy efficiency that do not result in a corresponding decrease in resource or energy use (Berkhout et al., 2000). Many researchers have addressed this issue and concluded that increasing energy efficiency will not be sufficient for reaching GHG emission reduction targets (Binswanger, 2001; Birol and Keppler, 2000; Brännlund et al., 2007; Herring and Roy, 2007; Hertwich, 2005; Roy, 2000). Whether a shift from fossil fuels to renewable energy will result in a corresponding decrease in the CF can be questioned in a similar way. Many renewable energy projects concern investments in energy production for new activities; such projects may simply add to the total energy use and not replace fossil energy use.

The feasibility of achieving increased carbon efficiency depends on available technology, market conditions, and the role governments play in promoting the shift towards a low-carbon economy. The IPCC distinguishes between three different 'emission reduction potentials' (Metz et al., 2007):

- *Market potential* is the reduction potential based on private costs and private discount rates. It reflects what is possible from a microeconomic perspective.
- *Economic potential* is the reduction potential based on social costs and benefits and social discount rates. It reflects what is feasible from a macroeconomic perspective.
- *Technical potential* is the amount by which it is possible to reduce GHG emissions by implementing a technology or practice that has already been demonstrated. It is

not limited by cost constraints, but by practical and physical limits, such as the available technologies and the rate at which these technologies may be employed (Van Vuuren et al., 2009).

The IPCC distinction between market, economic and technical potential for CF reduction can be a useful approach in the discussion of WF reduction. What is technically possible regarding WF reduction receives some attention in the *Water Footprint Assessment Manual*. It introduces the terms ‘zero blue WF’ and ‘zero grey WF’ for the industrial sector, referring to the possibility in most industries to fully close the water cycle and nullify chemical loads to ambient water bodies (Hoekstra et al., 2011). The huge variation in WFs for crop production shows that there is substantial potential for productivity increase and WF reduction (CAWMA, 2007; Mekonnen and Hoekstra, 2011a; Zwart et al., 2010). Examples of increased water efficiency in agriculture are use of drip irrigation instead of sprinklers (reducing the blue WF) and replacement of conventional by organic farming (reducing the grey WF). It would be useful to develop WF benchmarks for various activities (processes) and end products in order to set WF reduction targets by process and product.

The rebound effect discussed for the CF can be relevant when increasing water efficiency (McGlade et al., 2012). Reducing the WF of activities in a river basin will contribute to lessening the pressure on the basin’s water resources only when the reduced WF per unit of activity is not nullified by a simultaneous increase in production.

6.4.3 Reduction of footprints by changing production and consumption patterns

It is acknowledged that increasing efficiencies can be only part of the solution for reducing carbon and water footprints. Existing production and consumption patterns carry an inherent dependence on energy and water that cannot be addressed by increasing efficiencies alone. On the production side, for example, the international character of many supply chains leads to an inherent dependency on energy for transport. The energy demand can be reduced only if the supply chains are restructured such that less long-distance transport is involved. Existing production patterns are often inherently water-intensive as well; a good example is the common practice of intensive crop production in areas that are short of rain. The blue water footprint of crops can be reduced only if worldwide crop production is better aligned to where there is sufficient rain. Consumption patterns need attention as well. The relatively large contribution of meat and dairy consumption to humanity's CF – Steinfeld et al. (2006) estimate that the livestock sector is responsible for 18% of anthropogenic GHG emissions – can be reduced only if people reverse the current trend towards eating more meat and dairy. Replacement of a meat-heavy meal by a vegetarian or a meat-light meal will also help to substantially lower the WF (Mekonnen and Hoekstra, 2012). Not using first-generation biofuels or at least avoiding biofuels from the most water-intensive crops will help as well (Gerbens-Leenes et al., 2009b).

A reconsideration of production and consumption patterns is much more difficult than implementing measures to increase efficiencies because structural changes affect all sorts of vested interests, while, at least in the short term, efficiency gains benefit all parties. This explains why most of the attention of footprint reduction goes to efficiency and not to total production and consumption volumes. Both producers and consumers generally want to increase the levels of production and consumption, and efficiency gains can be instrumental in that. Because of the rebound effect, CF and WF reduction strategies that are focused on efficiency are likely to fail. Carbon and water efficiency increases need to be coupled with caps on total CFs and WFs.

6.4.4 Offsetting, neutrality and trading

The idea behind carbon offsetting is that one unit of CO_2-equivalent emitted into the atmosphere in one place from one activity has exactly the same contribution to climate change as another unit emitted elsewhere by another activity. As a result, a certain emission reduction always has the same effect, no matter how or where it is done (Bellassen and Leguet, 2007). Furthermore, there is the underlying idea that one can better reduce an emission elsewhere – if it is easier or cheaper – than reduce one's own emission (Bumpus and Man, 2008).

The practice of carbon offsetting was developed from the flexible mechanism included in the Kyoto Protocol that allows industrial countries to fulfil their obligations to reduce GHG emissions by purchasing emission reductions created by projects elsewhere (Barker and Ekins, 2004; Viguier et al., 2003). This mechanism was created as a result of a market logic, where demand and supply for reductions are created, priced and exchanged internationally and developed further with a parallel voluntary market. A typical example of the voluntary market can be found in the air transport sector: passengers can offset the emissions related to their flight by purchasing reduction credits elsewhere. Another example is offsetting emissions of energy use by buying carbon credits that are generated by renewable energy or forest planting projects (Bellassen and Leguet, 2007; Bumpus and Man, 2008).

Although the offsetting concept is based on some logic, it has unanswered questions that create confusion. Measuring, accounting and verifying are the main concerns, especially in voluntary offsetting. There are no clear definitions of what can count as an offset and no standardized methods to calculate the amount of CF that can be compensated for by a certain offset activity. Murray and Dey (2009), in their study of commercial websites that offer carbon offsets to companies and individuals, found that these enterprises do not have similar values for required offsets; do not have the same inputs and calculation methods; and, even for CF values that are close, do not have the same pricing of the offsets. They concluded that lack of standardization and transparency are the main problems in today’s voluntary offset market. Another concern about offsetting is the credibility of sequestration and other carbon credit projects. Finally, offsetting allows polluters to continue emitting, which is the wrong signal to be spreading regarding CF reduction. Together, these concerns place offsetting in a bad light. And there are many indications that both the formal (Kyoto Protocol) and voluntary mechanisms of offsetting have little effect on overall CF reduction (Spash, 2009). The absence of a closed accounting system makes it very difficult to measure the effectiveness of the whole system.

The idea of water offsets (or water credits) is gaining ground in the water community. However, as for carbon offsetting, the concept of water offsetting is still ill-defined. According to Hoekstra et al. (2011), in general terms it means taking measures to compensate for the negative impacts of the WF that remain after WF reduction measures have been implemented. But the two weak points of the definition are that (i) it does not specify which compensation measures and what level of compensation are good enough to offset a certain WF impact and (ii) it does not specify which impacts should be compensated and how to measure these impacts. An ill-defined concept can be easily misused – measures taken under the banner of 'offsetting' can potentially be a form of 'greenwashing' rather than a real effort aimed at full compensation. Another problem is that WFs and their associated impacts are always local; as has already been discussed in this report, in this respect the WF is markedly different from the CF. The idea of a global offset market does not make sense for water as it does for carbon. An offset for a WF should always occur in the catchment where the WF is located. This brings attention back to a company's own WF and does not allow it to simply buy an offset in a general compensation scheme (Hoekstra et al., 2011).

6.4.5 The interplay of actors

The challenge of CF reduction lies on the plate of various actors: governments, companies, investors, individual consumers and intergovernmental forums. To limit or reduce GHG emissions, national governments have been using various policies and measures: setting regulations and standards, applying taxes and subsidies, creating carbon credit markets, promoting voluntary actions, instigating research programmes and developing communication tools (Bumpus and Man, 2008; Kollmuss et al., 2008; Koteyko et al., 2010; Metz et al., 2007; Solomon et al., 2007; Stewart and Wiener, 2004; Wara and Victor, 2008). Four criteria are generally applied to evaluate the usefulness of each instrument: (i) environmental effectiveness; (ii) cost-effectiveness; (iii) distributional effects (including equity); and (iv) institutional feasibility (Harrington et al., 2004; Metz et al., 2007). It is important to note that CF-specific policies are not enough to reach CF reduction goals. Policies on poverty reduction, land use, trade, pollution, agriculture, food security and population should be considered altogether.

Regulation, legislation and standards are typical instruments used in environmental policy. The effectiveness of regulatory measures and standards depends on their stringency. They can be very effective and useful tools when businesses and consumers do not respond to calls for voluntary action. In the field of CF reduction, such policy instruments have successfully been implemented to promote energy efficiency: the European Union's action for the aviation industry and the US action for registry of emissions under the Consolidated Appropriations Act (2008) are two good examples of how regulation can play an important role (Courchene and Allan, 2008; Pandey et al., 2011). Several more examples can be found for the role of legislation, such as California's Global Warming Solutions Act (2006), which aims to reduce emissions and promote capping (Kossoy and Ambrosi, 2010), and the UK's Low Carbon Transition Plan (DECC, 2009). These examples show that regulatory standards are valuable in emission reduction. They are effective in stimulating consumers and industries to reduce their footprints.

In addition to regulatory intervention, governments can intervene in markets by applying taxes and subsidies, and they can promote consumption patterns that contribute to emission reduction. Taxes on emissions can be effective in terms of both environmental and cost concerns; for example, taxation in Denmark resulted in a 6% reduction and in Norway decreased emissions per unit GDP (Bruvoll and Larsen, 2004). However, they can create distributional and institutional problems (Metz et al., 2007). Taxes can also be ineffective for overall reduction as they provide polluters with an alternative: pay tax and pollute instead of invest in emission reduction. Furthermore, taxes are not popular policy tools, and political constraints and lobbying by industry can make them difficult to implement. Financial incentives are policy tools commonly used by governments to stimulate new technologies. Taxation and market creation also have important roles in technology development and innovation.

Through governmental regulations and policies, companies have started to realize that we are moving towards a carbon-constrained economy (Kleiner, 2007), and they are aware that they will soon face taxation, capping and other regulations related to their GHG emissions. CF calculation and emissions reduction is nowadays high on the agenda of many businesses. The main driver behind their rush to react is to enable continuation of their activities in a carbon-constrained economy and navigation of the new landscape to their advantage. But it is also a reaction to broad public concern over climate change and changes in consumer behaviour – a survey done in the UK showed that 44% of consumers are willing to pay more for low CF products (Pandey et al., 2011). Companies can react to all of these changes; they can see the new business opportunities in a carbon-based economy and create new markets for themselves: carbon trading, consulting, calculating, offsetting, and so forth. The role of business in strategies towards reduction of emissions is significant. Companies can change their production systems and invest in low-carbon technologies, but the financial burden associated with these actions can be immense and companies are not necessarily willing to take on this burden without legislation and changes in consumer choices pushing them to do so.

There is no doubt that communication tools are effective in CF reduction, but they are indirect and thus their effects are hard to quantify. Governments can use awareness and education campaigns to promote sustainable consumption and help consumers make better-informed choices. They can also influence producers to make production more sustainable (Stevens, 2010). In the case of the CF, communication instruments such as product labelling, carbon disclosure and public awareness campaigns are under discussion and several initiatives have been taken.

Carbon labelling of products is one of the tools that companies are starting to use to share CF information with consumers to help them make better-informed choices. Some governments, for example the French, are starting to think about regulation of product labelling. If labelling schemes are well defined and structured and use credible information, labelling could be an effective tool for creating incentives to move towards low-carbon products and supply chains (Brenton et al., 2009). Unfortunately, today’s CF does not provide such credibility because it has neither a standard definition nor a standard method of calculation.

With the growing awareness of global warming, individuals have become more concerned about their own actions. Individuals can lower their CFs by lowering their energy use at home and adapting their consumer and other behaviours; for example, buying locally grown food, travelling less, and travelling by bicycle or public transport (Frank et al., 2010; Kollmuss et al., 2008).

As can be clearly seen from the discussion above, societal response to the CF involves many actors taking their own steps – and by doing so they influence one another, which is an essential element in the overall response. A similar diversity of actor initiatives and mutual influences will probably develop for the WF, but we are at too early a stage to be able to reflect on the various governmental, corporate and civil society initiatives that are currently being taken in the WF field. The Spanish Government has made WF analysis mandatory in the preparation of river basin plans. Many other governments, for example that of South Africa, are in an exploratory stage (Hastings and Pegram, 2012). A great number of companies, most of them multinationals (e.g. Unilever [Jefferies et al., 2012]), have started to compute the WF for some of their products and to explore response strategies. More and more WF calculators are appearing online, the media is picking up the concept, and environmental organizations (e.g. the World Wildlife Fund and The Nature Conservancy) are starting to use the concept in their awareness campaigns.

Based on experience with the CF, it is hard to imagine progress in WF reduction without strong governmental and intergovernmental leadership. Legislation, regulation and standards will probably be necessary to stimulate consumers and industries to reduce their WFs. It will be important that the different WF components are treated individually, and in particular, strict regulations regarding the blue and grey WFs will be necessary to ensure optimal use and allocation of scarce water resources. Taxation can be a policy instrument; however, in reality taxation on one specific criterion is rare and politically very difficult to implement. Subsidies and financial incentives can be helpful instruments to promote new technologies and innovations, efficient use of water, reuse and recycling of water, and better wastewater treatment.

6.4.6 The water–energy nexus

There is a growing recognition that water policy and energy policy must be somehow related, because energy production requires water, and water supply requires energy. In the past, in fact until today, water and energy policies have mostly been disconnected. Whereas efforts have been undertaken to improve both water use efficiency and energy efficiency, we can observe two interesting trends. First, the water sector is becoming more energy-intensive – think, for example, of the energy needed for pumping groundwater from deeper and deeper sources, for constructing large inter-basin water transfer schemes and moving water through them, and for desalination of saltwater or brackish water. Second, the energy sector is becoming more water-intensive – especially because of the increasing focus on biomass as a source of energy (Gerbens-Leenes et al., 2009b). All energy scenarios for the coming decades show a shift towards an increased percentage of bioenergy, and thus an increasing WF (Gerbens-Leenes et al., 2012). The challenge is to search for coherent policies that reduce both CF and WF rather than developing energy policies that reduce CF but increase WF (like first-generation biofuels) and water policies that reduce WF but increase CF (like desalination).

6.5 Lessons to learn

As has been highlighted throughout the report, the CF and WF fields can inform each other in standardization, development, credibility, reduction strategies and policy tools. The main messages and lessons from the study of both concepts can be summarized as follows:

Definitions and methods

The use of the same definitions and methods for each of the CF and the WF across countries and sectors lends credibility to the concepts and is a good basis for setting real reduction targets and being able to verify them. The CF currently has competing and conflicting standards; standardization has failed due to a lack of coordination. In the case of the WF, the efforts of the Water Footprint Network to form a broad coalition of partners and develop a science-based global WF standard in an early stage of its practical use have been successful. The risk of future confusion from potentially competing initiatives (e.g. ISO [2012*b*]) is nevertheless present for the WF.

Reduction schemes

Reduction of the CF and WF through increasing carbon and water efficiencies is important, but the rebound effect must be given due attention. In energy studies, this effect is well known; in water studies the effect has had little attention to date. Alongside efforts to improve efficiencies, efforts to make societies less energy- and water-dependent are an essential ingredient of a good reduction policy.

Offsetting schemes

Offsetting schemes have inherent problems. The offsetting concept is ill-defined and can easily be misused, as illustrated in the sphere of CF offsetting. Without a clear definition, measures taken under the banner of ‘offsetting’ can potentially be a form of ‘greenwashing’ rather than a real effort aimed at full compensation. An offset of a WF should always occur in the catchment where the WF is located and in the period when it happens. This means that thinking in terms of general compensation schemes where one can simply ‘buy’ an offset is not applicable to the WF. In sum, offsetting is not a good option for a water scarcity mitigation strategy.

Regulatory standards

Regulatory standards have been useful and valuable for emissions reduction related to the CF, and governments should be aware that regulation can be an effective instrument in WF reduction as well. Regulation should aim to drive consumers and industries towards reducing their WF. Particularly strict regulations on reducing the blue and grey WF components can play a crucial role in optimal use and allocation of scarce freshwater resources, something that would be hard to achieve with awareness raising programmes and voluntary action alone.

Taxation

In theory, taxation could be a useful policy instrument in WF reduction strategies; however, as experience with the CF has shown, specific taxation on one criterion is rare and politically difficult to implement. Taxation in the WF area will also have additional complexity in implementation due to distributional problems. In sum, taxation does not look like a wise policy tool for WF reduction.

Multi-dimensional policies

For WF reduction, as for CF reduction, policies that address poverty, land use, trade, pollution, agriculture, food security and population should be considered together. CF- and WF-specific policies in isolation are not sufficient to meet reduction goals.

Product labelling

Although the CF and WF concepts can be used in product labelling as a communications tool to raise consumer awareness, their actual figures do not have sufficient information to allow consumers to make well-informed decisions on which products and services to purchase preferentially. Both footprints need to be compared to benchmarks, and for the WF, location and timing is relevant as well. Consumers are likely better served by labels that grade the sustainability of a product from low to high – criteria regarding the CF and WF can be integrated into such designations.

Leadership by government

Experience with the CF shows that for the development of comprehensive policy responses for WF reduction, strong governmental leadership and action will be required. Commitment and regulation are required at the national and international level. Engagement of business through production systems and individuals through consumer behaviour are also essential elements of policy response.

6.6 Conclusion

The CF has become a widely used concept by society, despite its lack of scientifically accepted and universally adopted guidelines. Stakeholders use the term with loose definition, according to their liking. The WF is becoming popular as well, and there is substantial risk that it will suffer the same problems as the CF. By attempting to understand the mechanisms behind the societal adoption of the CF, this report extracts lessons that may help reduce the risk of the WF losing its strict definition and interpretation.

Reduction and offsetting mechanisms have been applied and supported widely in response to the increasing concern about global warming. However, the effective reduction of humanity's CF is seriously challenged because of three factors. First, the absence of a unique definition of the CF means that reduction targets and statements about carbon neutrality are difficult to interpret; this leaves room for developments appearing better than they really are. Second, the focus on increasing carbon efficiency bears the risk of the rebound effect. Third, existing mechanisms for offsetting are extremely weak; it remains questionable whether or to what extent they actually contribute to the overall reduction of GHG emissions.

Responses for WF reduction are still under question. Water offsetting strategies will face the same problems as those of carbon, but there is a further problem: water offsetting can only be effective if it takes place at the specific location and in the specific period of time when the WF that is to be offset took place. The weakness of offsetting and neutrality mechanisms for the CF shows that applying those concepts to the WF is not a good idea. A more effective tool is probably direct WF reduction targets to be adopted by both governments and companies.

7 Integrating ecological, carbon and water footprint into a “footprint family” of indicators: definition and role in tracking Human Pressure on the Planet [6]

Abstract

In recent years, attempts have been made to develop an integrated footprint approach for the assessment of the environmental impacts of production and consumption. In this paper, we provide for the first time a definition of the “footprint family” as a suite of indicators to track human pressure on the planet and under different angles. This work has been developed under the 7th Framework Programme in the European Commission (EC) funded One Planet Economy Network: Europe (OPEN:EU) project. It builds on the premise that no single indicator per se is able to comprehensively monitor human impact on the environment, but indicators rather need to be used and interpreted jointly. A description of the research question, rationale and methodology of the ecological, carbon and water footprint is first provided. Similarities and differences among the three indicators are then highlighted to show how these indicators overlap, interact, and complement each other. The paper concludes by defining the “footprint family” of indicators and outlining its appropriate policy use for the European Union (EU). We believe this paper can be of high interest for both policy makers and researchers in the field of ecological indicators, as it brings clarity on most of the misconceptions and misunderstanding around footprint indicators, their accounting frameworks, messages, and range of application.

7.1 Introduction

7.1.1 Global environmental change: an overview

In the last few decades countries around the world have significantly changed, most experiencing economic growth, poverty reduction, and improved welfare (UNDP, 2006; UNEP, 2007). Such economic and social changes have been reached at the expense of the

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[6] Based on Galli et al. (2012)

planet's ecosystem preconditions and its ability to sustain life as demand for ecological assets has been increasing, standards of living improving and the size of the global economy and population growing unabated (Fisher-Kowalski and Haberl, 2007; Goudie, 1981; Haberl, 2006; Nelson et al., 2006; Rockström et al., 2009).

Global resource consumption and waste emissions have grown to a point where humanity now consumes at a faster pace than the Earth can regenerate or sequester (Catton, 1982; Ehrlich, 1982; Haberl et al., 2007; Hoekstra et. al, 2009; Meadows et al., 1972; Vitousek et al., 1986; Wackernagel et al., 2002; WWF, 2008;), and this mounting human pressure is at the root of many of the most pressing environmental problems and many of the factors contributing to the current global food crisis.

Many forests, particularly in tropical zones, are cut faster than they can regrow: 130,000 km^2 of forest have been destroyed per year for the last 15 years. Fish are caught faster than they can restock: 15% of ocean stocks were depleted in the same period (UNEP, 2007). World average per capita food and services consumption has grown during the last four decades (Turner, 2008); global extraction of natural resources (e.g., biomass, fossil fuels, metal ores, and other minerals) has increased by nearly 45% in the last 25 years (Behrens et al., 2007; Giljum et al., 2009a; Krausmann et al., 2009) coupled with a quadrupled world population over the last one hundred years. Many countries in arid and semi-arid regions of the world, especially Central and West Asia and North Africa are already close to or below 1000 m^3 $capita^{-1}$ $year^{-1}$, defined as threshold for water scarcity (Falkenmark, 1989).

Greenhouse gas (GHG) emissions are accumulating in the atmosphere, causing climatic changes and potential negative feedback on the health of ecosystems (Butchart et al., 2010; Haberl, 2006; Holdren, 2008; UNEP, 2007). Worldwide atmospheric concentrations of carbon dioxide (CO_2), Methane (CH_4), and nitrous oxide (N_2O), for example, have noticeably increased in recent decades, and they now considerably exceed the natural range over the last 650,000 years. With high confidence, scientists have concluded that these global average concentrations are due to human activities (IPCC, 2007).

In addition, the distribution of human-induced pressures is uneven in both its nature (Behrens et al., 2007; Haberl, 2006; Krausmann et al., 2009) and its geographic location (Erb et al., 2009a; Foley et al., 2005; Giljum et al., 2009a; Haberl et al., 2007; Halpern et al., 2008; Hertwich and Peters, 2009; Hoekstra and Chapagain, 2007; Kitzes et al., 2008a; Moran et al., 2008; Ramankutty and Foley, 1999; Ramankutty et al., 2002). On a per capita basis, people in high income countries consume much more natural resources than those in lower income countries as they are characterized by a higher affluence and an easier geographical and economic accessibility to resources. The transition from biomass-driven (agricultural) to fossil-fuel-driven (industrial) societies experienced by many high income countries (Haberl, 2006) has also determined a shift in the nature of the resources currently demanded and the ecosystem compartments that are now under the highest human-induced pressure.

As scenarios illustrate, these trends will likely continue in the future if measures are not taken to reduce this demand. For example, in a business-as-usual scenario, global extraction of natural resources could further grow by more than 50% by 2030 compared to today’s situation (Lutz and Giljum, 2009), and humanity’s demand on ecological assets (in ecological footprint terms) could equal two Earths worth of resources by 2040 (Moore et al., 2012). Up to two-thirds of the world population will then experience water scarcity over the next few decades (Alcamo et al., 2000; Vorosmarty et al., 2000) and slightly more than one billion people living in arid regions will face absolute water scarcity (less than 500 m^3 $capita^{-1}$ $year^{-1}$) by 2025 (Rosegrant et. al, 2002).

Acknowledging the increasing human impact on the natural world, more empirical measurements have thus to be sought to understand the driving forces behind these impacts and find ways to reduce impacts while maintaining economic and societal well-being.

The EC funded One Planet Economy Network: Europe (OPEN:EU) project, under which this work has been performed, originates from exactly this willingness to provide policy makers, particularly at EU level, with a tool that can help addressing the objectives of the EU Sustainable Development Strategy (SDS) and other policy strategies. This will help create a new forum for the visions, knowledge and interests of different stakeholders to help transform the EU into a One Planet Economy by 2050 (OPEN:EU, 2010).

7.1.2 The need for a set of indicators

As human societies and economies depend on the biosphere's natural capital for many underpinning functions (Best et al., 2008; Levin and Pacala, 2003), managing the planet's ecological assets must become a central issue for decision makers around the world. Despite an impending urgency to act, actions must be based on scientifically-sound accounting and integrated ecosystem approaches can potentially best inform decision makers as they enable to tackle multiple issues concurrently, and help avoid additional costs and inadvertently undoing progress in one sector by not accounting for direct and indirect implications of actions in another sector (Robinson et al., 2006; Turner, 2008). For this reason we believe a set of indicators is needed to account for the environmental consequences of human activities. The way human activities are linked to each other and affect different compartments of the biosphere has to be first understood (Vörösmarty et al., 2000; Weisz and Lucht, 2009).

Climate change, for example, is currently seen as the most impending environmental issue deterring societies from sustainability. Unfortunately, in the search for sustainability, decision makers have approached sustainable development through the climate change lens (Robinson et al., 2006), ignoring that the impact on the atmosphere is just one aspect of the human-induced environmental impacts. Looking at carbon in isolation – rather than a symptom of humanity's overall metabolism of resources – has made us blind to other dangers. The world's appetite for water, food, timber, marine, and many other resources is also relevant (Ewing et al., 2009; Fischer-Kowalski and Haberl, 2007; Giljum et al., 2009b; Krausmann et al., 2009; WWF, 2008).

By bringing together ecological, carbon, and water footprints into a single conceptual framework, this paper moves in the direction of an integrated ecosystem approach. However, it is acknowledged that these three indicators, even when used together as a "footprint family" of indicators, cannot provide a full sustainability assessment.

7.1.3 The need for consumer approach

If we lived in a world where countries produced and consumed all goods and services within the boundaries of their country, the distinction between consumption-based and production-based accounting would be unnecessary. But we live in a highly globalized world, where economies of scale and comparative advantage in certain areas exist, rendering trade and commerce highly valuable and "responsibility" over impacts much more complex. For instance, given the existing global environmental policy framework (e.g. Kyoto protocol) holding producers rather than final consumers responsible for human impact, a perverse incentive exists for industrialized countries to transfer high-impacting activities to the developing world by importing environmentally-inefficient goods and services, rather than achieve decoupling and changes in peoples' consumption behaviour in domestic economies (Galli et al., *forthcoming*). In recent years, consumption-based accounting (CBA) has become increasingly relevant as it provides several opportunities for policy and decision making processes (Wiedmann, 2009c) (e.g., quantifying trade relationships among countries, understanding the common although distinct responsibilities between producer and consumer countries, etc.).

The ecological, carbon, and water footprints emphasize the analysis of human demand from a consumer rather than a producer perspective. These indicators are not based on who produces a good or service but on the end-users that consume them. Due to their consumption-based approaches, these indicators present a quantifiable and rational basis on which to begin discussions and develop answers on the limits to resource consumption, the international distribution of the world's natural resources, and how to address the sustainability of the use of our ecological assets across the globe (Senbel et al., 2003).

However, if consumption-based accounting is to be accepted and used by decision makers, the tools to be used and their underlying calculation methodologies need to be reliable, robust and tested against relevant criteria (Wiedmann, 2009c).

7.2 Methods

Three indicators have been selected to be included in the footprint family: ecological, carbon and water footprint. Beyond the similarity in the name, these three methods have been selected because of their aims and underlying research questions. Their different, yet complementary, points of view allow for a more comprehensive tracking of the demand humans place on the planet and its set of ecosystem compartments.

7.2.1 Ecological footprint

The ecological footprint is a resource and emission[7] accounting tool designed to track human demand on the biosphere's regenerative capacity (Wackernagel et al., 1999a, 2002). It documents both direct and indirect human demands for resource production and carbon dioxide assimilation and compares them with the planet's ecological assets (biocapacity) (Monfreda et al., 2004; Wackernagel et al., 1999b).

By tracking a wide range of human activities, the ecological footprint monitors the combined impact of anthropogenic pressures that are more typically evaluated independently (carbon dioxide emissions, fisheries collapse, land degradation/ land-use change, etc.) and can thus be used to understand, in an integrated manner, the environmental consequences of the pressures humans place on the biosphere and its composing ecosystems. The ecological footprint can be applied at scales ranging from single products, to cities and regions, to countries and the world as a whole (Ewing et al. 2009).

Six key ecosystem services widely demanded by the human economy are tracked and associated with a type of bioproductive land: plant-based food and fibre products (cropland); animal-based food and other animal products (cropland and grazing land - agricultural land); fish-based food products (fishing grounds); timber and other forest

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[7] CO_2 is the only greenhouse gas accounted by the Ecological Footprint method.

products (forest); absorption of fossil carbon dioxide emissions (carbon uptake land[8]); and the provision of physical space for shelter and other infrastructure (built-up area).

Ecological footprint and biocapacity values are used to measure one main aspect of sustainability only: the human appropriation of the Earth's biological capacity. They analyse the human predicament from this distinct angle, motivated by the assumption that Earth's regenerative capacity might be the limiting factor for the human economy if human demand continues to overuse beyond what the biosphere can renew. In doing so, ecological footprint and biocapacity accounting take into account both the sustainability principles identified by Herman Daly (1990) as they identify the extent to which human activities exceed a) the availability of bioproductive land to produce resources and b) the availability of forests to uptake carbon dioxide emissions.

Both ecological footprint and biocapacity are resource flow measures. However, rather than being expressed in tonnes per year, each flow is expressed in units of area, annually necessary to provide (or regenerate) the respective resource flow. This reflects the fact that many basic ecosystem services and ecological resources are provided by surfaces where photosynthesis takes place. These surfaces are limited by physical and planetary constraints and the use of an area better communicates the existence of physical limits to the growth of human economies (GFN, 2010; Monfreda et al., 2004).

As bioproductivity differs between various land use types and countries, ecological footprint and biocapacity values are usually expressed in units of world average bioproductive area, namely global hectares – *g*ha (Galli et al., 2007; Monfreda et al., 2004; Wiedmann and Lenzen, 2007). Yield factors and equivalence factors are the two 'scaling factors' used to express results in terms of global hectares (Galli et al., 2007; Monfreda et al., 2004), thus allowing comparisons between various countries' ecological footprint and/or biocapacity.

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[8] It should be noted that the demand for the biosphere's carbon uptake capacity is usually also referred to as "carbon footprint", though this should not be confused with the "Carbon Footprint" methodology described in section 7.2.

7.2.2 Carbon footprint

The carbon footprint measures the total amount of GHG emissions that are directly and indirectly caused by an activity or are accumulated over the life stages of a product[9]. This includes activities of individuals, populations, governments, companies, organizations, processes, industry sectors, etc. In any case, all direct (on-site, internal) and indirect emissions (off-site, external, embodied, upstream, and downstream) need to be taken into account. More specific aspects such as which GHGs are included and how double-counting is addressed can vary (Wiedmann and Minx, 2008).

When applied to a country, the carbon footprint relates to consumption of goods and services by households, governments, and other 'final demand' such as capital investment. It also relates to the GHG emissions embodied in trade: the carbon footprint of a country is the sum of all emissions related to a country's consumption, including imports, but excluding exports. As such, the consumption-based perspective of the carbon footprint complements the production-based accounting approach taken by national greenhouse gas inventories, such as those considered by the Kyoto Protocol, which look at the emissions occurring on the territory of the country. Such consumption-based approach could encourage and facilitate international cooperation and partnerships between developing and developed countries, for example by prioritizing technology transfers, estimating financial transfers, and streamlining Clean Development Mechanisms (CDM). Moreover, from a communication point of view, CBA can be used to make consumers aware of the GHG emissions from their life-style and consumption choices. Likewise, CBA raises awareness of indirect emissions in governments and businesses.

Despite its name, the carbon footprint is not expressed in terms of area. The total amount of greenhouse gases is simply measured in mass units (kg, t, etc.) and no conversion to an area unit (ha, m^2, km^2, etc.) takes place. Any conversion into a land area would have to be based on a variety of assumptions that would increase the uncertainties and errors associated with a particular carbon footprint estimate.

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[9] Products include goods and services.

When only CO_2 is included, the unit is kg CO_2; if other GHGs are included the unit is kg CO_2-e, expressing the mass of CO_2-equivalents. Those are calculated by multiplying the actual mass of a gas with the global warming potential factor for this particular gas, making the global warming effects of different GHGs comparable and additive. In most cases, the six greenhouse gases identified by the Kyoto Protocol are included in the analysis: CO_2, CH_4, N_2O, HFC, PFC, and SF_6.

7.2.3 Water footprint

The water footprint concept was introduced in response to the need for a consumption-based indicator of freshwater use (Hoekstra, 2003). It accounts for the appropriation of natural capital in terms of the water volumes required for human consumption (Hoekstra, 2009). The water footprint concept is closely linked to the virtual water concept (Allan, 1998): the volume of water required to produce a commodity or service.

The water footprint looks at both direct and indirect water use of a consumer or producer. Three key water components are tracked in its calculation: the blue water footprint refers to consumption of surface and ground water (blue water resources); the green water footprint refers to consumption of rainwater stored in the soil as soil moisture (green water resources); the grey water footprint refers to pollution and is defined as the volume of freshwater required to assimilate the load of pollutants based on existing ambient water quality standards (Hoekstra et. al, 2009).

Water footprint can be calculated for a particular product, for any well-defined group of consumers (e.g. an individual, family, village, city, province, state, or nation) or producers (e.g. a public organization, private enterprise, or economic sector) and it is defined as the total volume of freshwater that is used to produce the goods and services consumed by the individual or community or produced by the business (Hoekstra and Chapagain 2008). The first assessment of water footprints of countries was carried out by Hoekstra and Hung (2002). A more extended assessment was done by Chapagain and Hoekstra (2004).

The water footprint concept aims primarily at illustrating the hidden links between human consumption and water use and between global trade and water resources management. This concept has been brought into water management science in order to show the importance of human consumption and global dimensions in good water governance (Hoekstra, 2009). The water footprint is a geographically explicit indicator, not only showing volumes of water use and pollution, but also the locations.

Water use is measured through the water footprint method in terms of water volumes consumed (evaporated or incorporated into the product) and polluted per unit of time. Depending on the level of detail that one aims to provide, it can be expressed per day, month, or year (Hoekstra et. al, 2009).

7.3 Discussion

7.3.1 Testing and comparing footprint indicators

According to van den Bergh's and Verbruggen (1999), the search for operational indicators should be guided by a number of specific criteria that indicators or set of indicators should meet. This has been a guiding principle in analysing the ecological, carbon , and water footprint, which have been tested against criteria such as scientific robustness, presence of a clear research question, policy usefulness, temporal and spatial coverage, etc. Similarities and differences among the three indicators have been also highlighted to show how the indicators overlap, interact, and complement each other.

As any indicator is, by definition, a simplification and modelling of a much more complex reality, sets of indicators such as the footprint family or alternative "baskets of indicators" could be more informative for policy makers (e.g., Best et al., 2008); however, their range of application as well as usefulness in tracking the functioning of a larger scope of the Earth's ecosystems has first to be tested before they can be actually adopted.

The outcomes of the indicators' testing phase have been reported in Table 7.1 below. Information reported in this table has then been used as starting points in defining the "footprint family" concept.

All three indicators were found able to represent the environmental consequences of human activities and complementary in assessing human pressure on the planet from a consumer-based angle; however, they are built upon different research questions and tell different stories.

The ecological footprint focuses on the aggregate demand that resource consumption places on the planet's ecological assets; thus recognizing the existence of limits to our growth and trying to measure them. The water footprint focuses on the human appropriation of natural capital in terms of fresh water volumes required for human consumption; it is primarily intended to illustrate the hidden links between consumption activities and water use. The carbon footprint focuses on the total amount of GHGs released due to resource-consumption activities; by complementing the production-based accounting approach taken by national GHG inventories, the carbon footprint provides a better understanding of humans' contribution to GHG emissions.

All three indicators are characterized by a wide spatial coverage and scale of applicability: they can all be applied to single products, cities, regions, nations and up to the whole planet. In terms of time coverage, the ecological footprint was found to be the most comprehensive as it covers a 1961-2006 time period, while values exist for the year 2001 and an averaged 1996-2005 period only for the carbon and water footprint, respectively.

The three indicators are all able to track both direct and indirect human demands, thus favouring a clear understanding of the 'hidden/invisible' human-induced sources of pressure. However, only the ecological and water footprint were found to be able to account for both the source (resource production) and sink (waste assimilation) capacity of the planet. The ecological footprint was then found to be the sole indicator able to provide a clear ecological benchmark (biocapacity) to test human pressure against. Setting a benchmark for the carbon footprint indicator is currently being considered in the OPEN:EU project (OPEN:EU, 2010).

Table 7.1. Footprint family - summary table .

	Ecological footprint	Carbon footprint	Water footprint
Research question	The amount of the biosphere's regenerative capacity that is directly and indirectly (i.e. embodied in trade) used by humans (namely ecological footprint) compared with how much is available (namely biocapacity), at both local and global scale.	The total amount of GHG emissions (CO_2, CH_4, N_2O, HFC, PFC, and SF_6) that are directly and indirectly caused by human activities or accumulated over the life stages of products.	The human appropriation of the volume of freshwater required to support human consumption.
Main message	To promote recognition of ecological limits and safeguard the ecosystems' life-supporting services enabling the biosphere to support mankind in the long term.	The consumption-based perspective of the carbon footprint complements the production-based accounting approach taken by national GHG inventories (e.g., those considered by the Kyoto Protocol).	The water footprint concept is primarily intended to illustrate the hidden links between human consumption and water use and between global trade and water resources management.
Data and sources	• Data on local production, import and export for agricultural, forestry and fisheries products (FAOSTAT, UN Comtrade); • Land use data (FAOSTAT, etc.); • Local and trade-embedded CO_2 emissions (IEA and others); and • Land yield (FAOSTAT) and potential crop productivity (provided by the FAO GAEZ model) – this data is needed to express results in units of global hectares.	• National economic accounts (supply, use, input-output tables); • International trade statistics (UN, OECD, GTAP and others); and • Environmental accounts data on GHG emissions (IEA, GTAP, and others).	• Data on population (World Bank); • Data on arable lands (FAO) and total renewable water resources and water withdrawals (FAO); • Data on international trade in agricultural (PC-TAS) and industrial products (WTO); and • Local data on various parameters such as climate, cropping patterns, soil, irrigation, leaching, water quality, pesticides and fertilizers rates, etc.
Unit of measurement	• Global hectares (gha) of bioproductive land. Gha is not a measure of area but rather of the ecological production associated with an area; and • Results can also be expressed in actual physical hectares.	• Kg CO2 when only CO2 is included or kg CO2-e when other GHGs are included as well; and • No conversion to an area unit takes place to avoid assumptions and uncertainties.	• Water volume per unit of time (usually m3/yr.) for the water footprint of processes; • m3/ton or litre/kg for the water footprint of products; and • Water volume per unit of time for the water footprint of a geographical area.

Indicator coverage	• Temporally explicit and multi-dimensional indicator that can be applied to single products, cities, regions, nations and the whole biosphere; • More than 200 countries for the period 1961-2006 are tracked (Ewing et al., 2009a); • Documents both direct and indirect human demands for both the **source** (resource production) and the **sink** (carbon uptake) capacity of the biosphere; • Provides a measure of both human **demand** and nature **supply**; • Provides a clear benchmark; and • It has a consumption-based point of view and thus considers trade.	• Multi-dimensional indicator that can be applied to products, processes, companies, industry sectors, individuals, governments, populations, etc.; • 73 countries and 14 regions for the year 2001 only are tracked (Hertwich and Peters, 2009); • Documents all direct and indirect GHGs emissions due to use of resources and products (**source**); • Measures the '**demand**' side only, in terms of the amount of GHGs emitted; and • It has a consumption-based point of view and thus considers trade.	• Geographically explicit and multi-dimensional indicator: it can be calculated for products, public organizations, economic sectors, individuals, cities and up to countries; • High-spatial resolution (0.5') 1996-2005 are tracked (Hoekstra and Mekonnen 2012); • Documents both the direct and indirect use of natural capital as a **source** (demand on blue and green waters) and as a **sink** (grey water to dilute pollution); • Measures the '**demand**' side only, in terms of freshwater consumed (by sources) and polluted (by type of pollution) by human activities; • No benchmark is provided; and • It has a consumption and production -based approach and considers trade.
Strengths	• Allows benchmarking human demand for renewable resources and carbon uptake capacity with nature supply and determining clear targets. • Provides an aggregated assessment of multiple anthropogenic pressures; and • Easy to communicate and understand with a strong conservation message.	• Allows for a comprehensive assessment of human contribution to GHG emissions; and • Consistent with standards of economic and environmental accounting. • Consistent emissions data available for the majority of countries.	• Represents the spatial distribution of a country's water "demand"; • Expands traditional measures of water withdrawal (green and grey waters also included); and • Visualizes the link between (local) consumption and (global) appropriation of freshwater. Integrates water use and pollution over the production chain.

Weaknesses	• Cannot cover all aspects of sustainability, neither all environmental concerns, especially those for which no regenerative capacity exists (including abiotic resources); • Shows pressures that could lead to degradation of natural capital (e.g. reduced quality of land or reduced biodiversity), but does not predict this degradation; and • Not geographically explicit. • Some underlying assumptions are controversial, though documented	• Cannot track the full palette of human demands on the environment • Additional impact assessment models are needed to analyse the impact of climate change at both national and sub-national levels; • Efforts needed to set up and update a system of MRIO tables and related environmental extensions; and • No benchmark is provided.	• Only tracks human demand on freshwater; • It relies on local data frequently unavailable and/or hard to collect. It suffers from possible truncation errors; • No uncertainty studies are available, though uncertainty can be significant; and • Grey water calculation heavily relies on assumptions and estimations.
Policy usefulness	• Measures ‘overshoot’ and identifies the pressures that humanity is placing to various ecosystem services; • Monitors societies’ progresses towards minimum sustainability criteria (demand ≤ supply); • Monitor the effectiveness of established resource use and resource efficiency policies; • Allows analysing the consequences of using alternative energies; • Communicate environmental impacts of different life-styles to the overall public; • Track pressure on biodiversity; and • Illustrates the unequal distribution of resource use and can be used to design international policies aiming at implementing contraction and convergence principles.	• Offers an alternative angle for international policy on climate change as it complements the territorial-based approach used by the UNFCCC; • Offers a better understanding of countries’ responsibility and could facilitate international cooperation and partnerships between developing and developed countries; • Can help design an international harmonized price for greenhouse gas emissions; and • Illustrates the unequal distribution of resource use and can be used to design international policies aiming at implementing contraction and convergence principles.	• Gives a new & global dimension to the concept of water management & governance; • Offers nations a better understanding of their dependency on foreign water resources; • Offers river basin authorities info on the extent to which scarce water resources are allocated to low-value export crops; • Offers companies a way to monitor their dependence on scarce water resources alongside their supply-chain; and • Illustrates the unequal distribution of resource use and can be used to design international policies aiming at implementing contraction and convergence principles
Complementary properties in the footprint family	• Uses a consumer-based approach to track human pressures on the planet in terms of the aggregate demand that resource-consumption and CO2 emissions places on the ecological assets.	• Uses a consumer-based approach to track human pressures on the planet in terms of total GHG emissions and human contribution to climate change.	• Uses a consumer-based approach to track human pressures on the planet in terms of the water volumes required for human consumption.

All three indicators illustrate the unequal distribution of resource use and/or related impacts between the inhabitants of different world regions and could thus be linked to policy debates in the development policy area, oriented at concepts such as “Contraction and Convergence,” “Environmental Justice,” or “Fair Share”.

A partial overlap exists between ecological and carbon footprint as human-induced CO_2 emissions are tracked by both methodologies. However, both methodologies go beyond the sole CO_2 investigation as the carbon footprint also tracks the release of additional GHGs (usually CO_2, CH_4, N_2O, HFC, PFC, and SF_6) and the ecological footprint expands its area of investigation by looking at human demand for food, fibres, wood products, etc.

For what concern ecological and water footprint, a partial overlap between these two indicators was found as water is tracked by both methodologies. But while direct and indirect freshwater requirements are clearly tracked by the water footprint indicator, the water issue is only indirectly tracked by the ecological footprint, which is able to provide limited information to back up water policies. As recognized by Kitzes et al. (2009), freshwater is a natural resource cycling through the biosphere, whose availability or scarcity influence the regenerative capacity (biocapacity) of the planet; however, water is not itself a creation of the biosphere for which the planet has a regenerative capacity. As such the direct ecological footprint of a given quantity of water cannot be calculated, though it is possible to measure the ecological footprint embedded in the provisioning of water (Lenzen et al., 2003). The combined use of ecological and water footprint within the footprint family suite of indicators is thus deemed to be the best approach to develop a multi-criteria decision making process and arrive at optimal decisions.

7.3.2 Definition of the footprint family

The combination of indicators presented in this research is not the first attempt at a combined footprint approach for the assessment of the environmental impact of productions (Giljum et al., 2009c; Niccolucci et al., 2010; Patrizi, 2009). However, the OPEN:EU project is to our knowledge the first attempt at clearly providing a definition to the footprint family of indicators in its wider range of applicability.

By looking at the amount of bioproductive area people demand because of resource consumption and waste emission, the ecological footprint can be used to inform on the impact placed on the *biosphere*. By quantifying the effect of resource use on climate, the carbon footprint informs on the impact humanity places on the *atmosphere*. Lastly, by tracking real and hidden water flows, water footprint can be used to inform on the impact humans place on the *hydrosphere*.

The footprint family is thus here defined as a set of indicators - characterized by a consumption-based perspective - able to track human pressure on the surrounding environment, where pressure is defined as appropriation of biological natural resources and CO_2 uptake, emission of GHGs, and consumption and pollution of global freshwater resources. Three key ecosystem compartments are monitored, namely the *biosphere*, *atmosphere*, and *hydrosphere* through the ecological, carbon , and water footprint, respectively.

The footprint family has a wide range of research and policy applications as it can be employed at scales ranging from a single product, a process, a sector, up to individual, cities, nations and the whole world.

The footprint family provides an answer to three specific research questions and helps to more comprehensively monitor the environmental pillar of sustainability. However, it is not yet a full measure of sustainability as several environmental (e.g., toxicity, soil quality and land degradation, nuclear wastes, etc.), economic, and social issues are not tracked.

7.3.3 The need for a streamlined ecological-economic modelling framework

Although grouped for the first time under a single conceptual framework – the footprint family - each of the three indicators is currently characterized by its own calculation methodology and accounting framework as reported in the scientific literature: carbon footprint accounts (Hertwich and Peters, 2009) utilize a Multi-Regional Input-Output (MRIO) model to allocate emissions to consumption; conversely ecological and water footprint have been historically calculated using process-based LCA data and physical quantities of traded goods (Hoekstra et al., 2009; Kitzes et al., 2008b).

In defining the footprint family concept, a need was identified to bring ecological, carbon , and water footprint together under a single streamlined ecological-economic modelling framework if the three indicators are to be used jointly as a suite of indicators. For instance, integrating ecological, carbon , and water footprint accounts with an MRIO modelling framework would strengthen the robustness and consistency of the footprint family concept as this would enable an inter-industry analysis of the linkages across multiple economies. Assessing trade-off would also be easier.

Currently, the Norwegian Institute of Science and Technology, Global Footprint Network, and University of Twente are working to develop such streamlined modelling framework, which will be then tested and explored for use in the OPEN:EU project (Ewing et al., 2012). In building such model, efforts are being made to go beyond the "classical" input-output/footprint approaches that have been proposed in the past. Particularly, a multi-regional input-output model will be used and a high level of detail in commodity classification ensured while integrating existing accounts for ecological and water footprints within a more complete (but less detailed) MRIO framework: direct footprint requirements will be calculated with a process-based type of approach and indirect footprint requirements via a monetary model (Ewing et al., 2012).

However, such integration process conveys both pros and cons. While the integration of environmental and economic accounts is extremely valuable, approximations are required as part of the calculation to utilize economic flows as a proxy for the physical flows. Moreover, the use of Input-Output tables with footprint indicators causes a decreased time coverage (as MRIO models usually refer to a single year only) and resolution (because of the shift from detailed product-level to aggregated sectoral-level assessments). The benefit of a purely physical flow accounting approach—where economic data is not introduced into the models—is that the product resolution is much higher and these accounts track the physical flows directly. However, the weakness of this approach is that physical flow datasets are less prevalent and developed than the economic flows related to the same products and the physical flow data sets only track goods, excluding services. These physical flow accounts also do not completely link with the supply chain or the economic activities that are driving the resource or waste flows (Ewing et al., 2012).

7.4 The role of the footprint family in the EU policy context

7.4.1 Resource use trends at EU level

The European Union uses 20% of what the world's ecosystems provide in terms of fibres, food, energy, and waste absorption (WWF, 2005). Home to only 7% of the world population, Europe's demand on the biological capacities of the planet has risen by more than 70% since 1961 (Ewing et al., 2009; WWF, 2008).

Inhabitants of Europe have per capita resource consumption levels around 3 to 5 times higher than those of developing countries (Giljum et al., 2009a; WWF et al., 2008). While extraction of natural resources has stabilized in Europe over the past 20 years, imports of raw materials and products have significantly increased (Dittrich, 2009; Weisz et al., 2006). Residents of the global South thus continue to bear the negative impacts of EU profligate consumption: a) these negative impacts stem from extraction and processing of raw materials (such as metal ores, timber, agricultural products, etc.) as the material basis for products consumed in Europe; b) the global South bears an over proportional burden from waste and emissions originating from European consumption. For example, each EU-27 citizen emitted on average 10.2 t of GHG emissions (in CO_2-equivalents) in 2009 (EEA, 2009). This number has been falling in the past years due to efforts to decrease domestic emissions, however, GHG emissions embodied in European imports from other world regions have risen rapidly in the past 15 years (Bruckner et al. 2010; Peters and Hertwich, 2008; Wiedmann et al., 2008). Europe is also expanding built-up and urban areas for housing, industrial, and commercial sites and transport networks. From 1990 to 2000, more than 4.000 km² of agricultural and pasture land were transformed into built-up land, increasing anthropogenic pressures on biodiversity (EEA, 2006).

Fresh water is increasingly becoming a global resource, driven by growing international trade in goods and services. Europe, particularly Western Europe, is one of the largest virtual water importers in the world with an import of 152 Gm^3 $year^{-1}$ (Chapagain and Hoekstra, 2004); the people of Europe have higher water footprints per capita than the world average (especially in south European countries such as Greece, Italy and Spain, 2300-2400 m^3 $year^{-1}$ per capita). Additionally, European counties are more dependent on foreign water resources for their consumption activities. In some European countries external water footprints contribute to 50-80% of the total water footprint (e.g. Italy, Germany, the UK, and the Netherlands) (Chapagain and Hoekstra, 2004).

A shift to a more sustainable future, therefore, requires a qualitative and quantitative understanding of the drivers in play, as well as a significant mobilization and behavioural change of actors and institutions from all sides of the public, private, and consumer spheres. A sustainable future for Europe can be achieved only by building an economy that respects environmental limits (including biodiversity) while also improving social and financial health.

7.4.2 The EU policy context

Acknowledging the need to understand and account for the main drivers behind Europe's use of natural resources and related environmental impacts, the European Commission (EC) launched several strategies calling for such assessments including, among others, the Sustainable Development Strategy (SDS), and the Thematic Strategy on the Sustainable Use of Natural Resources.

However, despite widespread support in different EU policy fields for the general ideas of increasing resource efficiency and reducing negative environmental impacts, little concrete action has been taken. No quantitative targets have been formulated for increased resource productivity or for a reduction of environmental impact of resource use in any of the main EU policies. Most resource policy documents remain on a general level of declarations of intent, without detailing those concrete policy measures that should be implemented to achieve the formulated objectives. A strategy to systematically adjust EU policies to promote resource productivity in the EU is far from being realised.

The One Planet Economy Network: Europe (OPEN:EU) project originates from the willingness to answer the renewed EU Sustainable Development Strategy (SDS) call for the development of indicators able to capture the full complexity of Sustainable Development. To this end, the concept of footprint family has been introduced and its potential policy usefulness explored and reported in the section below.

7.4.3 Policy usefulness of the footprint family

The review of the three footprint indicators has helped to clearly define each indicator's specific-although-limited research question. It has also highlighted that taken alone each of these indicators reflects only one part of the whole "sustainability" picture and cannot be used as a stand-alone indicator. For instance, although the issues tracked by the ecological footprint are clearly relevant to sustainability, the messages that can be derived from ecological footprint accounting may not provide the full information relevant for EU policy goals (e.g. no information is provided on health issues or the consumption of non-renewables resources). The ecological footprint alone does not reveal all important facts about environmental impacts and the same is true for the water and carbon footprints.

Because of its limited scope (human appropriation of freshwater resources), the water footprint alone is in fact not sufficient to inform policy makers and consumers about the (un)sustainability of human natural resource use, and could benefit from being integrated with other indicators. The carbon footprint is designed to calculate all direct and indirect GHG emissions from all types of sources and it can be considered complete for such GHG accounting. However, the range of human-induced pressures on the environment is much broader that just GHG emissions and thus, if used in isolation, the carbon footprint is not adequate to address issues related to sustainability and anthropogenic pressures.

Conversely, the joint use of ecological, carbon , and water footprint as a suite of indicators (footprint family) provides a better overarching picture of the human pressure on the natural environment and its key compartments (namely biosphere, atmosphere, and hydrosphere), where indicators compensate for each other flaws and complement each other in assessing trade-offs as well as real pressure reductions rather than just pressure shifting from one compartment to the others.

A small suite of indicators is deemed to be the best approach for measuring the overall environmental impacts of production and consumption. Although not all aspects are included when these three indicators are used (e.g. no indication of ecosystem disturbance, land use quality and/or impact on biodiversity, no tracking of the depletion of non-renewable resource stocks, no information on people health and well-being, no information on air quality), the use of the footprint family still provides information on sustainable development to a satisfactory extent (Knoblauch and Neubauer, 2010).

Here the footprint family has been tested against some of the main European (and international) policy objectives in an attempt to identify which indicator can best address the specific environmental issues EU policy makers have to face, as well as the value added of addressing such issues with the whole footprint family suite of indicators. Outcomes of this "policy-testing" have been summarized in Figure 7.1; however, it has to be noted that only the most relevant policy and policy fields have been considered in this analysis.

Concerning the EU Sustainable Development Strategy (SDS), the ecological, carbon , and water footprint are partly suitable to inform policy makers as they contain information relevant for strategy but do not cover all the policy fields covered by the strategy. Although extended in the range of applicability, even the footprint family is not able to inform on all the different aspects of the EU SDS. In particular, out of the seven key challenges included in the EU SDS, only three (climate change and clean energy; sustainable production and consumption; conservation and management of natural resources) can be informed by the footprint family, while the other four (sustainable transport; public health; social inclusion, demography and migration; and global poverty and sustainable development challenges) are not covered. The footprint family is thus only partially suitable to inform policy makers on EU SDS.

The same is true for the EU 6th Environmental Action Plan (6EAP). Some of the aspects are covered through the ecological, carbon , and water footprints but none of the indicators covers all aspects. In particular, the following four key priority areas are relevant for the 6EAP: climate change; nature and biodiversity; environment, health and quality of life; natural resources and wastes. The ecological footprint is suitable to inform on nature and biodiversity, natural resources and wastes, and only partly on environment, health and quality of life. The carbon footprint is at least partly suitable to inform about climate change (it only directly informs about GHG emissions and not climate change). The water footprint is suitable to partly inform about natural resources and waste since water is also a natural resource. The aspect of health and quality of life is covered by none of the indicators.

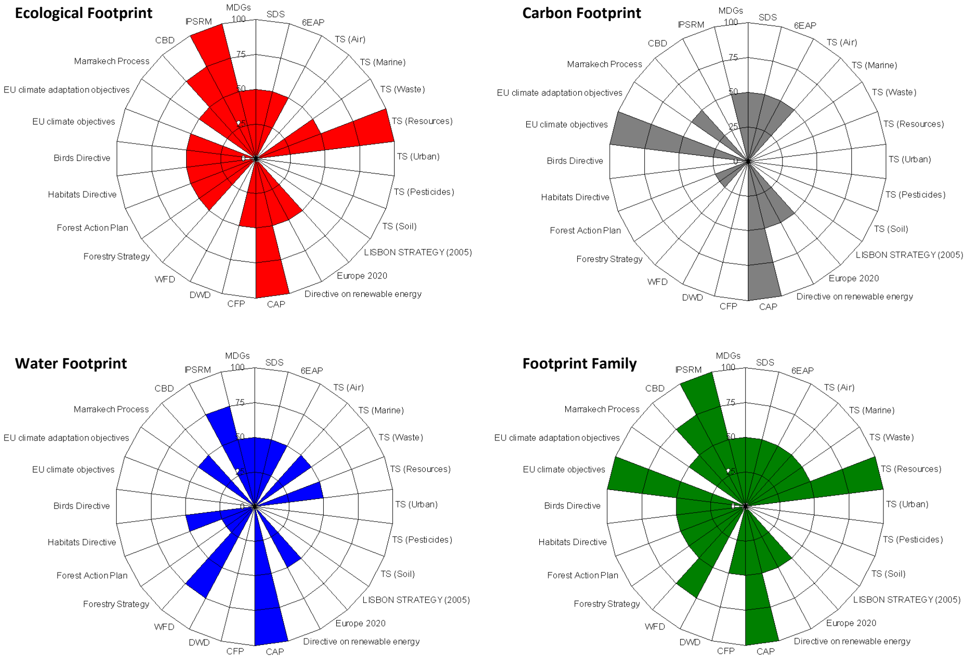

Figure 7.1. Indicator-Policy Radar. It summarizes the range of applicability and the depth of the assessment for each of the footprint indicators as well as the whole footprint family. For any given policy, the radar highlights whether the indicator is able to address such policy fully (100), sufficiently (75), partially (50), marginally (25) or not at all (0).

Four of the seven Thematic Strategies (TS) within the 6EAP can be partly informed by the footprint family: the carbon footprint partly informs on the Thematic Strategy on air pollution (TS Air), the water footprint partly informs on the Thematic Strategy on the marine environment (TS Marine), and the ecological footprint can partly inform the Thematic Strategy on the prevention and recycling of waste (at least indirectly through addressing the overexploitation) (TS Waste). The Thematic Strategy on the sustainable use of natural resources (TS Resources) can be fully informed by the ecological footprint and as regards water by the water footprint. The remaining three thematic strategies (urban environment, sustainable use of pesticides and soil protection) cannot be informed by the single footprint indicators neither by the footprint family.

The 2005 Lisbon Strategy primarily focused on social and economic aspects and thus none of the footprint Indicators is suitable to inform policy makers for this strategy. Conversely, the Europe 2020 Strategy includes environmental and climate targets and thus the ecological, water, and carbon footprint are partly suitable to inform on the headline target of the renewed strategy (e.g., carbon footprint informs on the headline target to reduce the GHG emissions and the ecological and water footprint inform on the flagship initiative on a “Resource Efficient Europe”). However, most of the headline targets and flagship initiatives focus on issues that cannot be informed by the footprint family (e.g. employment rates, share of early school leavers, poverty, youth, internet, etc.).

The Directive on renewable energy (Directive 2009/28/EC), the Forestry Strategy as well as the Forest Action Plan are all resource related policies and the ecological footprint was found to be informative to address them (Knoblauch and Neubauer, 2010). However, since the indicator is an aggregated one, it can only help decision makers grasp the big picture and understand the links between such policies but it may not be suitable to inform policy makers concerning a specific resource (e.g. forests).

The various water use policies - especially those addressing water scarcity and resource productivity - can partly be informed by the water footprint (e.g., Water Framework Directive - WFD). However, to derive conclusions for practical policies from the number provided by the water footprint, one would need to compare the existing water resources in the considered country with the water use numbers provided by the water footprint. As regards water pollution, specifically the grey water footprint informs on the water quantity that would be needed to dilute water polluted for the use of production or providing services to neutralize the pollution. The water footprint was found to be not informative regarding the Drinking Water Directive (DWD).

The Common Fisheries Policy (CFP) defines the type and amount of fish that each Member State is allowed to catch. Since the ecological footprint includes the fishing ground biocapacity and footprint in its calculation, it is suitable to addresses the CFP. However, due to its aggregate nature, it can help decision makers grasp the big picture but it may not be suitable to inform policy makers concerning a specific resource (e.g. fish stocks) as it does not deal directly with policy-responsive issues. Moreover, the current fishing grounds ecological footprint and biocapacity trends are not able to show fish stock depletion; additional research is needed (Ewing et al., 2009; Kitzes et al., 2009) and ongoing (Hartman et al., 2010) to improve such calculation.

The climate related policies reported in Figure 7.1 can all be partly informed by the carbon footprint as it measures emissions for six main GHGs; still carbon footprint values need to be interpreted in context (i.e. their reduction needs to be analysed in a time series) to derive information on climate change. It has been suggested that the most serious consequences of global warming might be avoided if global average temperatures rose by no more than 2 °C above pre-industrial levels. Recent research suggests that it would be necessary to achieve stabilization below 400 ppm of carbon dioxide in the atmosphere to give a relatively high certainty of not exceeding 2 °C and a concentration of 350 ppm carbon dioxide has been advocated as an appropriate level. As of April 2010, carbon dioxide concentration in the Earth's atmosphere was 391 ppm by volume; this renders any additional emissions as 'unsustainable' and the carbon footprint informative to cover the issue.

Regarding the Convention on Biological Diversity (CBD), the ecological footprint has been officially included in the list of indicator that the Biodiversity Indicator Partnership (BIP) is using to monitor world governments progress toward the 2010 biodiversity target set by the CBD in 2002. The BIP approaches biodiversity with a Pressure-State-Benefit-Response framework and the ecological footprint is one of the pressure indicators used (Butchart et al., 2010). The ecological footprint is thus related to the biodiversity issue in that it is a measure of the human pressure on ecosystems and biodiversity; time series ecological footprint assessments constitute a way to measure how this pressure has changed over time. The carbon and water footprint were found not informative for CBD.

All of the footprint Indicators as well as the footprint family are partly suited to inform policy makers on the UN Millennium Development Goals (MDGs). Particularly, Goal 7 (Ensure Environmental Sustainability) refers to resource use/deforestation, climate change and drinking water – all of which are issues that can be informed by the three indicators. Because of its ability to analyse the extent of the global ecological assets each country is using compared to what is available, the ecological footprint can inform on issues such as equity in resource accessibility and use; this, in turn, can be used to partially inform on Goal 8 (Develop a global partnership for development). However, since MDGs are quite broad in their scope, the indicators are not suited to fully inform policy makers on all issues addressed therein. All other MDGs cannot be informed by the footprint family.

The International Panel for Sustainable Resource Management (IPSRM) observes, among others, exploitation of resources. The ecological footprint is thus fully suitable to inform stakeholders concerned with the panel, while the water footprint informs about the issues related to water use and productivity. By contrast, the carbon footprint is not dealing with this topic and, consequently, cannot inform stakeholders on the issue.

The Marrakech Process deals with sustainable consumption and production issues. The ecological, water, and carbon footprint are also dealing with consumption and production issues: the first concerning the bioproductive land appropriation, the second concerning water use, and the third regarding the emissions perspective and they can therefore inform the process. Moreover, with the development and implementation of a streamlined MRIO-footprint model (Ewing et al., 2012), the footprint family will better inform these processes via linking the information on consumption and production, i.e. traces the footprint along the full supply chain.

Since the adoption of the Health Check, new challenges have been highlighted for the future Common Agricultural Policy (CAP), which brought environmental issues in a stronger focus of European agriculture: climate change, the need for better water management, the protection of biodiversity, and the production of green energy. Activities and measures resulting from these challenges and further debated within the currently ongoing CAP reform process can fully be informed by the ecological, carbon , and water footprint as well as the whole footprint family.

The Directive on the conservation of natural habitats and of wild fauna and flora (Directive 92/43/EEC) - Habitats Directive - aims to protect different land and water habitats and species. This directive can be marginally - and only indirectly - informed by the ecological and water footprint as these indicators show the aggregate pressure humans place on various ecosystems and habitats. The carbon footprint was found not informative for the habitats directive.

Last but not least, the Directive on the conservation of wild birds (Directive 2009/147/EC) - Birds Directive - is about establishing protected areas for birds thus focusing on land protected for them. The policy can consequently be marginally - and only indirectly - informed by the ecological footprint – as a measure of growing human pressure - but not by the other indicators.

7.5 Conclusion

The footprint family of indicators introduced in this study is intended to assist policy makers as well as academics, CSOs, and other practitioners in understanding the many diverse pressures human activities place on the planet. It represents a quantifiable and rational basis on which to begin discussions and develop answers on the limits to natural resource and freshwater consumption, greenhouse gas emissions, as well as on how to address the sustainability of natural capital use across the globe.

The need for developing such a family of indicators originates from the understanding that, when used in isolation, each of the indicators considered in this paper is able to capture just one limited aspect of the full complexity of sustainable development. As a result, there is a lack in the indicators realm of methods and tools with which to fully illustrate the links between economic growth and environmental degradation to policy makers, CSOs and the public.

The footprint family proposed here can thus be used to improve researchers' ability to track the current resource use and the impact this use generates, highlight the main drivers of resource use (therefore providing information on the areas where actions are needed), suggest solutions, and quantify the outcomes of specific policies undertaken to reduce the negative environmental impacts of natural resource use. However, relevant sustainability-related topics including human health and well-being still cannot be tracked with the footprint family.

The three indicators selected are all characterized by the capacity to represent the environmental consequences of human activities, though they are built around different research questions and tell different stories. The ecological, carbon , and water footprint have to be regarded as complementary in the sustainability debate and the footprint family as a tool able to track human pressures on various life-supporting compartments of the Earth (*biosphere*, *atmosphere*, and *hydrosphere*). The use of the footprint family of indicators thus eases a multidisciplinary sustainability assessment and it also emphasizes the strengths and dissipates the weaknesses of each indicator.

If Europe, or any other region, is to truly address sustainable development then decision makers need multiple tools and sets of indicators. In reducing resource consumption while improving economic well-being, all compartments (biosphere, atmosphere, and hydrosphere) need to be taken into account and trade-offs understood to avoid additional cost, or worse, inadvertently undoing progress in one sector by not accounting for direct and indirect implications of actions in another sector.

Of the three indicators, the ecological footprint was found to have the widest spectrum of applicability, though only the Thematic Strategy on the sustainable use of natural resources and the International Panel for Sustainable Resource Management were found to be fully and directly addressed by this indicator. Conversely, the carbon footprint was found directly able to address the EU Climate Objectives, though its range of applicability was found to be very narrow. The water footprint was found to be sufficiently informative for the EU water policies. As a consequence, the footprint family was found to be suitable for tracking human pressure on the planet and informative for policy and decision makers. Although not yet comprehensive and unable to track some relevant economic and social issues, the footprint family was found to cover a wide-enough spectrum of policies and it is believed to provide information on sustainable development to a satisfactory extent.

8 Discussions and conclusion

The motivation of this thesis has been to explore the application of the water footprint methodology within the context of governmental policy and corporate strategy. Two perspectives are addressed under one framework because solutions to freshwater scarcity and pollution require not only better and effective governmental policy but also responsible corporate engagement. Because of this connection, water footprint assessment can be an effective tool in facilitating communication between governments and businesses in response to shared concern over unsustainable water use.

Chapters 2 to 5 of this thesis aimed to illustrate how water footprint assessment can yield meaningful information to governments and businesses that can feed and facilitate discussion about sustainable water use. With the case studies in Chapters 2 and 3, we showed how companies can employ the water footprint to assess their operational and supply-chain water consumption and pollution including the relevant spatial and temporal dimensions. Our analysis showed that a detailed supply-chain assessment should be included in business water accounting as the bulk amount of water used by businesses is in their supply-chain. This is particularly important as common practice in business water accounting is mostly restricted to the analysis of operational water use and consequently reduction targets are formulated with regard to operational water use. Understanding the pressures that they put on water resources can help companies to mitigate the negative impacts of their water use and the risks imposed on the business. This study revealed that the knowledge about blue, green and grey components of the water footprint and the precise locations and timing of water use is essential for formulating mitigation policies. This thesis showed that water footprint assessment provides a comprehensive tool for businesses to measure their water use and impacts which can help them identify risk, drive improvement and sustain their businesses.

Linking specific consumer products in a country to water problems elsewhere is still uncommon in governmental thinking about water policy. With Chapter 4, a case study from governmental perspective, we visualized this link. The analysis presented in this chapter included both water footprint accounting and sustainability analysis from both the perspective of national production and the perspective of consumption. One of the conclusions of this study is that analysing the water footprint of consumption is an important addition to looking at the water footprint of production, because imported consumer products can substantially contribute to water scarcity and pollution in watersheds outside the country. Understanding the impacts in these watersheds is necessary to understand the true sustainability national consumption. It is essential to look at how much water is used and when it is used in order to assess the impacts on local ecosystems. The analysis in this chapter showed that water footprint assessment can give valuable information on how water resources of a nation are used, its dependency on water resources of other nations and impacts of its consumption behaviour outside its borders.

Another application of the water footprint is presented in Chapter 5 on water footprint scenarios, to show how consumer choices and other parameters will affect the level of water consumption and pollution globally. This gives important information to governments that can support the formulation of corrective policies at both national and international levels, and can help to set priorities for the years ahead in order to achieve sustainable and equitable use of the world’s water resources.

The reduction of humanity's water footprint depends on the combination of what governments, businesses and consumers will do and how their different policies will reinforce (or counteract) one another. This is addressed in Chapter 6 which compares carbon and water footprints and shows how lessons from carbon footprint can be drawn to benefit how policies are developed for the water footprint. Experience with the carbon footprint suggests that for the development of comprehensive policy responses for water footprint reduction, strong governmental leadership and action will be required. Commitment and regulation are required at the national and international level. Engagement of business through production systems and individuals through consumer behaviour are also essential elements of effective change.

The water footprint by itself captures just one aspect of the full complexity of sustainable development. This is addressed in Chapter 7 in which a ‘footprint family’ of indicators is presented. The analysis concludes that no single indicator is able to comprehensively monitor human pressure on the environment, but indicators rather need to be used and interpreted jointly. Therefore, policy makers should interpret the information provided by water footprint assessment carefully and consider the connections and trade-offs between all aspects of sustainability in their decisions.

Future outlook

This thesis contributes to a better understanding of the role of governments and businesses in managing humanity's water footprint. However, it is limited to practical aspects of how to apply the methodology of water footprint accounting and sustainability assessment. It does not examine alternatives for policy responses that can be applied in practice. Extending this study to the elaboration of specific types of impacts related to the water footprint and to the examination and evaluation of various sorts of response measures by governments and companies is recommended for future research. How to set quantitative water-footprint reduction targets and benchmarking for businesses can be logical next steps.

The thesis considered sustainability of production and consumption from a water resources perspective. Other environmental concerns need to be added for achieving a more comprehensive understanding of sustainability. Besides, the sustainability analysis in this thesis focuses on the environmental aspects of sustainability, leaving out social, economic and institutional aspects. This is to be added in further research. Another line of new research can aim to understand the role of other stakeholders in water governance, like consumers, local communities and civil society organizations.

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