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Flows of virtual land and water through global trade of agricultural products

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Marianela Fader

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Scientific Abstract

Land, green and blue water (precipitation water stored in the unsaturated soil and irrigation water, respectively) are essential inputs for the agricultural sector and thus the foundation of food supply. In spite of this, pollution, climate change, population growth and changes in lifestyle, among other factors, are putting additional pressure on these resources. Nevertheless, globalization allows the consumption of products that were produced in other countries and thus did not need local land and water resources. Consequently, along with agricultural products, countries virtually trade the land and water that were needed for their production. "Virtual" means in this context that the resources are not physically embedded in the products. This PhD thesis advances the research field on virtual flows through a number of innovative objectives: a) assessing water productivities at present, and for the first time, also under climate change conditions, while identifying the determinants of the spatial patters, b) analyzing agricultural yields globally under climate change conditions, for the first time accounting extensively for uncertainties in development and climate scenarios, c) assessing comprehensively international virtual resources flows together with water footprints, separating for the first time the green and blue components, and including the first analysis on virtual land flows and savings, and d) offering the first analysis on current and future dependence on *ex situ* land and water resources, accounting for population growth and improvements in agricultural productivities.

These analyses are based mainly on calculations from the biosphere and hydrology model Lund-Potsdam-Jena model (LPJmL) which uses climate, CO_2 concentrations, land use patterns and soil structure as inputs to simulate, at 0.5° resolution and daily time steps, sowing dates, photosynthesis, phenology, maturity, production and carbon stocks of 11 crop functional types, an additional commodity group called "other crops" and managed grasslands. Also carbon and water fluxes between different compartments (atmosphere, plants, soil) are modeled. LPJmL offers thus an excellent opportunity to overcome widespread low spatial and temporal resolution while accounting in a process-based way for the coupling between agrosphere and hydrosphere.

Despite the model and input uncertainties discussed in each chapter, and besides the intrinsic uncertainty about future developments, some general conclusions can be drawn:

The high-resolution analysis of crop water productivities and agricultural yields for the present time showed that there are high potentials for improvement in productivities in tropical and subtropical regions, especially in Africa, and in Southeast Asia. Current spatial patterns of agricultural yields and water productivities result from many interacting factors, including climate, soil and agricultural management. Water stress and length of growing periods seem to be important determining factors for water productivity.

Temperature and precipitation change tend to have negative effects for water and land productivities (by the middle of the century, global average yield decrease up to 13%; virtual water content increases of ~10-20% in many areas), with the exception of the northern high latitudes. However, future development of yields and water productivities will depend mainly on the degree of realization of the positive effects of CO_2 fertilization. In general, yield increases and higher water productivities are expected if full CO_2 fertilization is accounted for (by the middle of the century, global average yield increases of 8-22% and virtual water content decreases of ~15-30% in many areas).

Coupling of LPJmL with trade data from the COMTRADE database showed that global water and land productivities are higher under current trade patterns than in a hypothetical world of self-sufficient countries (8% and 5% respectively). And current patterns of virtual land and water flows lead to global water and land savings (~263 km^3 and 41 Mha). This means that self-sufficiency of agricultural products would require higher use of water and land.

Water footprints are defined as the amount of water consumed domestically or in other countries to produce the agricultural products consumed by the inhabitants of a country. Spatial patterns of water footprints differ depending on the computed unit (km^3 or m^3 cap^{-1}) and the type of water considered (green, blue, total). Generally external water footprints, i.e. the amount of water consumed in other countries, were shown to be much lower than internal ones (the external blue water footprint represents 6% of the total blue water footprint; the external green water footprint represents 16% of the total green water footprint). Green water dominates the production of crop products, both for domestic consumption and for export (84% of total water consumption is green, 94% of the external water footprint is constituted by its green component). In general, green virtual water flows and water footprints are also higher than blue ones. Moreover, countries with high water footprints affect mainly the water availability in their countries, since they have low ratios of external to internal water footprints.

According to my analysis, 62 countries, mainly situated in Africa, are not able to produce the crops they consume currently due to land and water constraints, even considering potentials for cropland expansion. Thus, currently, ~900 million people depend on *ex situ* land and water resources. Considering increases in crop productivity leaves 14-21 countries (corresponding to 300-400 million people) unable to meet the land requirements for self-sufficiency in the present time; these are thus depending on virtual land imports.

7400 to 1000 million people might depend on *ex situ* water and land resources by 2090, considering SRES A2r population growth and depending on the degree to which improvements in agricultural productivities are achieved and cropland areas are extended. Population growth will have to be accompanied in Africa, the Middle East and Andean countries by a strong cropland expansion and water consumption increase, as well as improvement of agricultural productivities, if they do not want that the proportion of their population depending on external land and water resources increase to levels higher than 50%, or in case of lack of financial means, having one of two people suffering from mal- or undernourishment. Nevertheless, some countries will experience higher dependence on *ex situ* water and land resources in the future, even if they expanded cropland, increased water consumption and improved agricultural productivities.

All in all, this PhD thesis enhanced system-analytic understanding of agricultural water fluxes and land use, and particularly the role of international trade therein, based on most up-to-date and comprehensive dynamic modelling approaches and guided by novel perspectives on the global water system and its components (green, blue, virtual water). Thereby, it comes to the conclusion that current production of food is not longer exclusively connected to local resources' availabilities. Instead of that, virtual flows, and especially dependence on *ex situ* land and water resources, are widespread and co-shape the global picture and regional patterns of the human appropriation of water and land.

Kurzzusammenfassung

Für die Nahrungsmittelproduktion benötigt der landwirtschaftliche Sektor fruchtbares Land und Regen- bzw. Bewässerungswasser (Grün- bzw. Blauwasser). Durch Umweltverschmutzung, Klimawandel, Bevölkerungswandel, veränderte Lebensstile, etc. geraten diese Ressourcen jedoch mehr und mehr unter Druck. Doch der internationale Güterhandel ermöglicht den Erwerb von Produkten, die anderweitig produziert worden sind und somit keine lokalen Land- und Wasserressourcen benötigt haben. Folglich ist der Handel landwirtschaftlicher Güter implizit ein virtueller Handel dieser Land- und Wasserressourcen, die für die Produktion der Handelsware verbraucht wurden. Virtuell heißt in diesem Kontext, dass die Handelswaren dieses Land und Wasser nicht in physikalischer Form enthalten. Der Forschungsbeitrag dieser Doktorarbeit ist a) die Analyse der Wasser- und Landnutzung sowohl für die heutige landwirtschaftliche Produktion als auch, erstmalig, unter Einbeziehung von Klimawandelbedingungen; b) die umfassende Untersuchung des internationalen virtuellen Land- und Wasserhandels, letzteres erstmalig in Grün- und Blauwasser unterschieden; c) die erstmalige Analyse von Abhängigkeiten von externen Land- und Wasserressourcen.

Meine Untersuchungen zeigen, dass die landwirtschaftlichen Land- und Wasserproduktivitäten – das sind die landwirtschaftlichen Erträge sowie die Erntemenge pro verbrauchte Wassereinheit – räumlich sehr stark variieren. Entwickelte Länder haben im Allgemeinen eine höhere Land- und Wasserproduktivität. Diese Produktivitäten werden jedoch durch den Klimawandel modifiziert. Meine Simulationen zeigen, dass eine Temperaturerhöhung sowie Veränderung der Niederschläge in den höheren, nördlichen Breiten zu einer Verbesserung der Produktivitäten führen, während in den restlichen Regionen die Produktivitäten abnehmen. Zudem bewirkt die Erhöhung von Kohlenstoffdioxidkonzentrationen in der Atmosphäre einen sogenannten Düngungseffekt für Pflanzen, der vielerorts die negativen Konsequenzen einer Temperaturerhöhung und Veränderung der Niederschläge ausgleichen könnte. Ob dieser Effekt eintritt, hängt jedoch von mehreren Faktoren ab, wie z.B. der Nährstoffverfügbarkeit im Boden, dem Wasserstress, etc.

Der Wasserfußabdruck ist die gesamte Menge an Grün- und Blauwasser, die ein Land für die Herstellung der Konsumgüter seiner Bevölkerung sowohl auf eigenem Territorium als auch im Ausland verbraucht. Meine Quantifizierungen zeigen, dass der im eigenen Land verbrauchte Wasseranteil (interner Wasserfußabdruck) in nahezu jedem Land größer als der externe Anteil ist. Auch verbraucht die landwirtschaftliche Produktion fast überall mehr Grün- als Blauwasser, sei es für den Eigenbedarf oder für den Export. Darüber hinaus untersucht diese Arbeit Länder mit einem hohen Wasserfußabdruck und zeigt erstmals, dass sie vor allem eigenes Wasser verbrauchen.

Nach meinen Berechnungen führt der internationale Handel zur Einsparung von Wasser- und Land, denn ohne globalem Handel landwirtschaftlicher Güter wären zusätzlich rund 263 km^3 Wasser sowie 41 Mio. Hektar Land für Eigenproduktion notwendig. Der Handel ist jedoch mit Abhängigkeiten verbunden, denn meine Untersuchungen ergeben, dass rund 900 Mio. Menschen (v.a. in Afrika und dem Mittleren Osten) von externen Land- und Wasserressourcen abhängig sind. Bei Annahme eines hohen Bevölkerungswachstums könnten 2090 ca. 1000-7400 Mio. Menschen von diesen Ressourcen abhängig sein, je nachdem, ob landwirtschaftliche Gebiete ausgedehnt und Produktivitätsverbesserungen verwirklicht werden können oder nicht. Erhöhte Abhängigkeiten von externen Land- und Wasserressourcen sind vor allem in Nordafrika und dem Mittleren Osten zu erwarten.

Síntesis de divulgación

Para la producción de alimentos el sector agrícola requiere suelos fértiles y agua dulce – sea ésta proveniente directamente de precipitación o suministrada a través de riego. La presión sobre estos recursos está creciendo rápidamente debido por ejemplo a la contaminación del medio ambiente, al cambio climático, a cambios en el estilo de vida y al crecimiento demográfico. Sin embargo, el comercio internacional ofrece la posibilidad de consumir bienes que han sido producidos en otros lugares y por ende no han necesitado de los resursos naturales locales. Así, cuando los productos agrícolas son comercializados internacionalmente, se comercia con ellos, de manera virtual, el agua y el suelo que han sido usados para su producción. La palabra virtual significa en este contexto que tales recursos no forman parte física de dichos productos. Esta tesis doctoral aporta: a) un análisis extensivo de la productividad de la tierra y del agua en la agricultura actual, y, como elemento innovador, bajo condiciones de cambio climático, b) una investigación detallada del comercio internacional de tierra y agua virtual, separando por primera vez los componentes de agua de precipitación y de riego en forma explícita, y c) el primer análisis del grado de dependencia de cada país de las importaciones agrícolas.

Los resultados indican que la productividad del suelo y del agua, o sea el rendimiento agrícola y la cantidad de cosecha por unidad de agua consumida, varían mucho en el espacio. En general los países desarrollados presentan productividades de agua y suelo más elevadas que los no desarrollados. Sin embargo, estas productividades serán modificadas por el cambio climático. Las simulaciones muestran que el aumento de las temperaturas y el cambio en la cantidad y el régimen de las precipitaciones causarán en las latitudes medias y altas del hemisferio norte una mejora en la productividad, en el resto de las regiones, una desmejora. Así y todo, el aumento de las concentraciones de dióxido de carbono en la atmósfera produce un efecto fertilizante para las plantas que podría contrarestar las consequencias negativas del cambio climático en muchas regiones. No obstante, es incierto si tal efecto realmente se producirá, ya que éste depende de factores varios, tales como la disponibilidad de nutrientes en el suelo, el estrés hídrico, etc.

La „huella de agua“ o “huella hídrica” es la cantidad de agua de lluvia y de riego que un país usa en su propio territorio y en otros países para la producción de los productos consumidos por su población. Los resultados de esta tesis indican que la parte de esta huella que se refiere al uso interno, o sea en el propio territorio, es generalmente mayor que la parte externa. Además, en casi todos los países se consume más agua de precipitación que de riego, ya sea en la producción para consumo interno o para la exportación. Los países que presentan huellas hídricas por encima del promedio consumen sobre todo agua dentro de su propio territorio.

Según los resultados de esta tesis, el comercio internacional disminuye el uso de agua y tierra fértil, ya que si todos los países produjeran por sí mismos los productos que consumen actualmente, se necesitaría un uso adicional de ~263 km^3 de agua y 41 millones de hectáreas de tierra. Sin embargo, dicho comercio está vinculado a dependencias: las simulaciones indican que actualmente hay alrededor de 900 millones de personas (sobre todo en Africa y el Medio Oriente) dependientes de recursos de agua y tierra no situados en sus países. En el año 2090 podrían ser entre 1000 y 7400 millones, si asumimos un escenario de alto crecimiento demográfico y dependiendo por un lado, de la expansión de las áreas agrícolas, y por otro lado, de la medida en que la productividad agrícola mejore en el futuro. En especial en el norte de Africa y el Medio Oriente más personas podrían depender de recursos naturales externos en el futuro.

Contents

List of Tables

List of Figures

Chapter 1

General Introduction

1.1 Background

Water is the foundation of life. It is not only the major component of the human body and of Earth surface, but also an essential part of all known forms of life and a vital input for the production of our life support: food. Besides the fact that water resources development is linked to economic progress, water was also the source of modern civilization, since the first settlements flourished around rivers and major waterways.

The importance of water is also reflected in three recent, internationally important events: on the one hand, the United Nations General Assembly approved a resolution to make access to water a basic human right in July 2010, linking water to human dignity and the right to life. On the other hand, two NASA's billionaire missions were successful, with the Phoenix Mars Lander finding water on Mars by mid of 2008 (Watanabe, 2008) and the Moon Mineralogy Mappers finding water in lunar dust by the end of 2009 (Weselby, 2009). The latter two reflect how important is water for us, since huge amount of financial resources are inverted in finding it outside our home planet.

Moreover some significant reports have led the attention of the general public and the political spheres to the topic water. One of the most prominent ones was the UN World Water development Report 3, published in 2009. Among others, it states that not resolving the water crises, which is linked to the crises of climate change, energy and food supply and troubled financial markets, might lead to increasing political insecurity and conflicts (World Water Assessment Programme, 2009).

The term water crisis is frequently used to refer to an increasing water demand in all sectors in combination with regionally decreasing water availability (de Villiers, 2000, see Fig. 1.1). Demand is increased due to changes in lifestyle, such as diet towards more meat and changes in hygienic behavior, increased food demand due to population growth and economic development, expansion of biofuel plantations, industrialization, evapotranspiration increase due to higher temperatures and expansion of irrigated areas (Mauser, 2007; Gleick, 1993). Regional water availability is modified due to contamination, new water infrastructure such as dams and channels, land use change, aquifers overexploitation as well as due to climate change, with more frequent extreme events, acceleration of the water cycle, changes in precipitation patterns and changes in atmospheric circulation, such as more frequent El Niño events and variations in the Monsoon regime (Bates et al., 2008; de Villiers, 2000; Rost et al., 2008). This is why

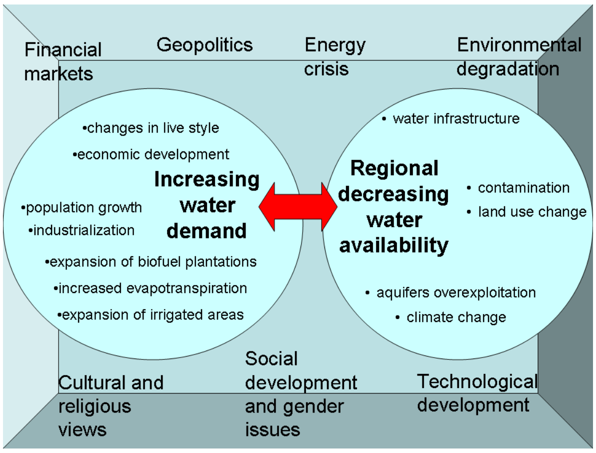

Figure 1.1: Water crisis: the conflict between increasing water demand and regional decreasing water availability within the context of other influencing factors.

knowing how much water we need to produce food is vital for taking the right development, adaptation and mitigation decisions.

Besides being vital for humans, water is a renewable resource that "flows" between different Earth compartments through the water cycle (see next section), is spatially highly variable and is too bulky to be transported (van der Zaag and Savenije, 2006). This is why the amount of accessible freshwater and its consumption by humans are also very variable as well. Water availability, suitable temperatures and availability of productive land, in combination with human management, determine the potential for agricultural production and thus the capacity of a nation to produce food for their inhabitants and for international trade.

The exceptional importance of freshwater and productive land is also reflected in their use by the agricultural sector (see also section 1.1.2):

- Water withdrawal for agriculture constitutes ~70% of total water withdrawal. The global share for industry and municipalities is only a small part, 20% and 10%, respectively (Comprehensive Assessment of Water Management in Agriculture, 2007). However, the situation has a strong spatial pattern (Fig. 1.2), with the highest withdrawal for agricultural use in South East Asia and the highest withdrawal for industry and households in the developed countries, especially in the US (Gleick, 2003).
- Cropland and pasture land occupy together ~34% of the Earth surface (Ramankutty et al., 2008). Roads, infrastructure and settlements appropriate ~1% of land surface (Erb et al., 2007). The rest is mainly covered by natural ecosystems.

Local water and land use is however only a part of the total use, since globalization offers the possibility to overcome spatial land and water scarcities through international trade (Yang et al., 2003). The water and land that was used to produce agricultural goods is thus virtually traded with those products (Allan, 1997), and, hence, importing agricultural goods instead of producing them domestically saves water and land of the importers (Chapagain et al., 2006). This leads to the fact that water footprints – i.e. the amount of water needed to produce the products consumed by the inhabitants of a certain country – have an internal component (the water consumed domestically) and an external component (the water consumed abroad) (Hoekstra and Chapagain, 2006; Hoekstra and Hung, 2002).

This PhD thesis will deal with virtual land and water flows, looking at the productivity of land and water use in current agriculture and under climate change conditions, and quantifying the magnitude of current virtual flows, savings, water footprints and countries' dependence on virtual imports.

Before detailing more specifically the objectives of this work (section 1.3) and describing the contributions of the author to each chapter (section 1.4), the next three sections offer an overview of the water cycle and stocks, the current levels of agricultural land and water use, and the state of virtual water research.

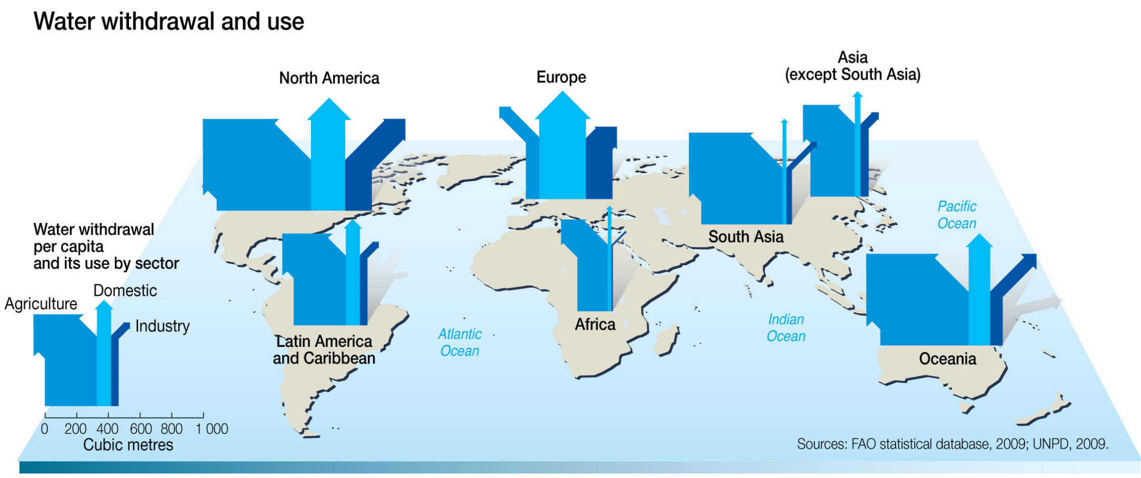

Figure 1.2: Amount of water withdrawal and its use for agriculture, industry and households in each continent (UNEP/GRID-Arendal, 2010).

1.1.1 The water cycle and freshwater stocks

Almost all freshwater is stored in ice caps (68.7%, 24,064,000 km^3) and groundwater (30.1%, 10,530,000 km^3). Only a small part of it, 0.3%, is surface water, mainly available in lakes (Shiklomanov, 1993). But water is not static, it is in constant movement across the Earth compartments – land, biosphere, atmosphere, hydrosphere, cryosphere – in its different states (liquid, solid, gaseous).

Ocean water is heated by the sun and evaporates, rising, cooling and thus building after condensation clouds that move through the atmosphere and precipitate partly on land surface, as snow or rain. Precipitation can run off and end up once again in the sea through river discharge or be temporarily stored in water reservoirs (dams, lakes). Water can also become part of seasonal or permanent snow and ice bodies. From them it can sublimate directly back into the atmosphere or melt, running off downstream (Evans, 2011).

Water can also infiltrate and after that percolate to groundwater or become interflow, sourcing downstream back to the surface as freshwater spring to run off once again. Water can also be evaporated from plant and soil surface back to the atmosphere or can be taken by plant roots and be transpired. Water stored in groundwater or surface bodies can be taken by humans to be used for industry, as irrigation water or drink water (Fig. 1.2). After use it goes back to the cycle, running off, infiltrating or being evapotranspired (Evans, 2011).

Concerning the quantities involved in the described processes, about 505,000 km^3 are evaporated annually from oceans, only 10% from this amount precipitate on land. Together with precipitation from local sources, total precipitation on land ranges between ~106,000 and 119,000 km^3 (Shiklomanov, 1993; Gruber and Levizzani, 2008). ~35% from this amount is returned to the oceans as rivers, ground and glacial runoff (Shiklomanov, 1993).

The natural water cycle and freshwater stocks – and actually almost all natural processes on Earth – have been modified by humans. For example land use change, fossil groundwater exploitation and dam construction have altered plant evapotranspiration and discharge of many rivers (Scalon et al., 2007; Haddeland et al., 2007; Boucher et al., 2004; Gordon et al., 2005; Foley et al., 2005). Water and air pollution have also changed the atmospheric and freshwater chemistry, leading to changes in condensation, precipitation and freshwater availability (Ma et al., 2010; Singare et al., 2011; Larssen et al., 2006). Finally, anthropogenic climate change will modify the whole water cycle and especially precipitation regimes, including the frequency of extreme events (Huntington, 2006; Bates et al., 2008; Gerten et al., 2008).

The next section offers a short overview about the current degree of human appropriation of water and land resources.

1.1.2 Water and land use in agriculture

The start of agriculture is frequently set about 10,000 years ago with the transition from the nomad way of life as hunter-gatherers to settlement, accompanied by cultivation of crops and domestication of animals (Mazoyer and Roudart, 2006; Tauger, 2011). Since then a lot happened in this sector, including expansion of cultivation areas, development of different agricultural tools and techniques, expansion of irrigation and a more or less steady increase in production, though with high variability.

However, the quickest and deepest developments started in the early 20th century with the invention of the Haber process that allowed synthesizing ammonia from the air which in turn made possible the production of nitrate fertilizers by oxidation (Modak, 2002). Agricultural productivity stayed however relatively constant or even declined due to economic depression and war until the second half of the 20th century where the green revolution allowed to strongly increase agricultural production (Tauger, 2011). In only few years yield were dramatically increased mainly through breeding of varieties with higher harvest indexes, irrigation expansion and the use of chemical fertilizers and pesticides (Mazoyer and Roudart, 2006; Tauger, 2011). Also developments in the transport sector and agricultural machines, such as tractors, container shipping, refrigeration, rail and highways facilitated this trend (Mazoyer and Roudart, 2006). In this period the area equipped for irrigation nearly doubled and agricultural areas increased by 24% (Molden et al., 2007a). Also water demand rose dramatically in this time and large hydrologic projects were performed for hydropower, irrigation and flood control (Gleick, 2003). Total water withdrawal rose from 579 km^3 in 1900 to 2,526 km^3 in 1970 and to 3,788 km^3 in 1995 (Shiklomanov, 1999). These developments are a part of the strong human influence on the Earth's environment leading to global change and can thus be regarded as symptoms of the fully prevalence of the Anthropocene Era (Steffen et al., 2004).

Today there is still great potential for increasing water and land productivities in many regions of the world, but yields show also in some regions some leveling off (Cassman et al., 2003; Gleick, 2003). The following paragraphs give an overview of the current agricultural water and land use.

Agriculture, as said above is the main user of productive land, blue water (water in rivers, aquifers and reservoirs, as irrigation water) and green water (precipitation stored in the unsaturated soil of agricultural areas) (Falkenmark et al, 2009). Figure 1.3 shows an overview of current water (blue and green) consumption of crops, as sum of soil evaporation, interception and plant transpiration. Water consumption is highest in India, China, Pakistan and the US, and lowest in the African and South American Tropics (Siebert and Döll, 2010).

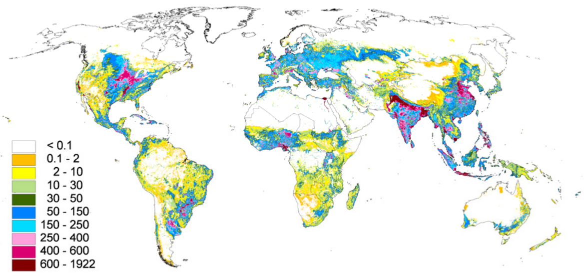

Figure 1.3: Blue and green water consumption mm yr^{-1} (i.e. evaporation, transpiration and interception) of irrigated and rainfed agriculture (Siebert and Döll, 2010).

Irrigated area covers ~278 Mha globally and produces 33% of global agricultural production (Siebert et al., 2006; Portmann et al, 2010). These areas are widespread all over the world with a clear predominance in South East Asia, especially in India, Pakistan and China (Fig. 1.4).

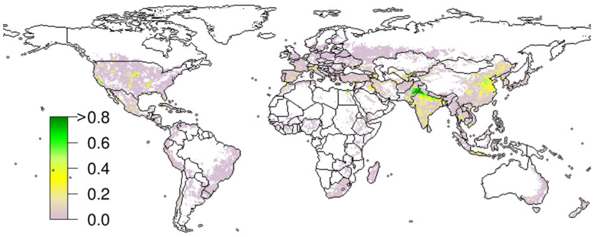

Figure 1.4: Irrigated areas as fraction of total grid-cell area as in Fader et al., 2010.

Water withdrawal for irrigation amounts currently ~2,700 km^3. From this, a part is lost on the way to the fields, another part infiltrate in the fields and ~930-1,550 km^3 (~57% of withdrawal) is evapotranpired from the irrigated fields (Comprehensive Assessment of Water Management in Agriculture, 2007; Hoff et al., 2010; Rost et al., 2008). Additionally, green water evapotranspiration from irrigated areas amounts up to 1,700 km^3, depending on the model and land use dataset used (Comprehensive Assessment of Water Management in Agriculture, 2007; Hoff et al., 2010; Fader et al., 2011). Naturally these amounts vary a lot from site to site, depending on climate, soil characteristics and the crops and management used. It is also worth noting that irrigation does not always occur from surface water. It is estimated that 114 Mha of irrigated land are equipped for groundwater irrigation, this is equivalent to 38% of area equipped for irrigation (Siebert et al., 2010). Globally, total water consumption from these areas is estimated to be ~545 km^3 (43% of total consumption) (Siebert et al., 2010). This is why it is essential to account for this source of irrigation water, especially in countries where it is widespread, like in China, India and the US (Siebert et al., 2010).

Rainfed cropland covers ~1,258 Mha globally (see compilation of land use dataset in Chapter 2) and produces 67% of global agricultural production. Agricultural plants on rainfed areas evapotranspire ~4,590-5,090 km^3 green water (Siebert and Döll, 2010; Hoff et al., 2010). Rainfed areas are found in all countries between 60° northern latitude and 40° Southern latitude with the exceptions of high mountains, dense rainforests and deserts (Fig. 1.5).

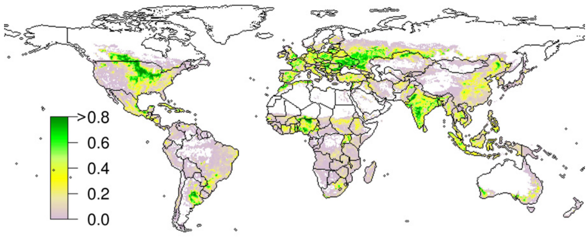

Figure 1.5: Rainfed areas as fraction of total grid-cell area as in Fader et al., 2010.

Pastures cover ~2,800 Mha globally (Ramankutty et al., 2008) and evapotranspire ~9,780-13,240 km^3 green water annually (Hoff et al., 2010). Especially in Australia, Patagonia, Kazakhstan and Mongolia pastures are the dominant land use (Fig. 1.6).

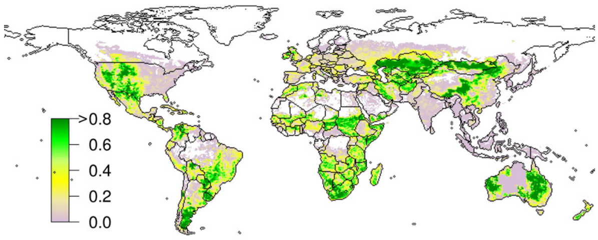

Figure 1.6: Pasture areas as fraction of total grid-cell area as in Fader et al., 2010.

These land and water use patters are not static. For example, in the last years and in response to changes in diets towards more meat consumption, many agricultural areas were switched to production of seeds and cereals for feed and natural ecosystems were converted to pastures (see e.g. Margulis, 2004; Dros, 2004). Also the expansion of biofuel plantation is changing current land and water use patters (e.g. Lapola et al., 2010; de Fraiture et al., 2008). Future changes in agricultural land and water use can also be induced by scientific advances, for example by agricultural experimental research which is currently split in two main directions: exploring the potentials of agroecological, organic and sustainable techniques for a more productive but non-degrading agriculture (see e.g. Chapell and

La Valle, 2009; Badgeley et al., 2007), and genetic engineering searching for more productive, pest and diseases resistant, high yielding varieties that do not lose all harvest under extreme whether situation, such as drought (see e.g. Fereres and Connor, 2004; GMO Compass, 2006a; GMO Compass, 2006b). Regarding water, especially the refinement of hydroponics and water desalination are leading the current scientific efforts (Lopez-Gunn and Llamas, 2008; Bradley and Marulanda, 2001).

1.2 State of research

Virtual water is the water consumed to produce goods and services. In agriculture it is hence the blue and green water that is evapotranspired on the fields during the growing period. It is called *virtual* because it is not physically embedded in the products. The virtual water concept was first mentioned by Prof. Anthony Allan as a tool for water-scarce Middle East countries to overcome their water limitation (Allan, 1997). Following this idea, the so called "virtual water content" started to disseminate as measure to quantify the amount of water used to produce one unit of a commodity (see e.g. Earle, 2001; Renault, 2002).

Based on virtual water content calculations, some research groups started to quantify "virtual water flows" or "virtual water trade", i.e. the amount of virtual water imported and exported from/to a country due to international trade (Hoekstra and Hung, 2002; Yang and Zehnder, 2002; Yang et al., 2006). Also "water savings" were quantified at country and global level as the water that would have been needed to produce import goods domestically (e.g. Renault, 2002; de Fraiture et al., 2004; Yang et al., 2006). Based on virtual water trade calculations, and inspired by the analyses on ecological footprints, Hoekstra and Hung (2002) developed and analyzed the so called "water footprints" as a measure for the water consumption level of a country, group, company or society.

These studies had however several shortcomings: the publications of Allan (1997) and Renault (2002) had rather a conceptual or exemplary character without systematic quantifications of the indicators. The study by de Fraiture (2004) was limited to cereals. The calculations of Earle (2001) were limited to Southern Africa and used data on agricultural yields and water consumption at yearly time scale and country resolution. Hoekstra and Hung (2002) and Yang et al. (2006) used the climate of the capital city as representative for the whole country, based calculations on yields averaged at country-scale and assumed optimal crop growth and only one variety per crop when calculating water consumption (not considering water stress even in rainfed agriculture). Water footprints in Hoekstra and Hung (2002) included only blue water consumption.

Some posterior analyses presented improvements in some aspects, for example Chapagain and Hoekstra (2004) and Hoekstra and Chapagain (2006) included green water consumption in water footprint calculations, but still showed only total water footprints, without differentiating between the blue and the green components. Moreover, they still used country-averaged climate and yield data, and did not accounted for any water stress, as was also the case in Chapagain et al. (2006) and Chapagain and Hoekstra (2008).

The first efforts to overcome the roughness in spatial resolution in virtual water flows analyses were made by Liu et al. (2009) and Hanasaki et al. (2010), who calculated grid-cell virtual water contents and virtual water flows with the EPIC and the H08 models, respectively. However, Hanasaki et al. (2010) did not account for coexistence of different crops in a grid-cell, did not have a link between plant growth (and yields) and the hydrology model H08 and focused only on virtual water exports, leaving virtual water imports, footprints and savings unquantified. Liu et al. (2009) did not quantified sowing and harvesting dates in a process-based manner (they calculated instead growing periods systematically and chose then the one with the highest yields). They neither calculated water savings and water footprints.

Thus, all the studies mentioned above left important research gaps:

(1) Virtual water contents were described and exposed without analyzing their determining factors.

(2) The consequences of climate change for virtual water contents were not approached.

(3) The link between bio- and hydrosphere was lacking, i.e. water stress was not taken into account for the calculations of virtual water contents, flows and footprints.

(4) Water footprints analyses did not differentiate between the green and blue components and not all differentiated between the internal and external components (i.e. the water consumed in the own country and the water consumed in other countries, respectively).

(5) The question of countries' dependence on external water resources had been approached without considering potentials for increases in water productivity and population change in the future (Hoekstra 2009b; Hoekstra and Hung, 2002).

(6) Even though agricultural production is linked to water *and* productive land, the land resource was not considered in any study, neither in the virtual flows nor in the dependence question.

In sum, three years ago there was a clear need for a more comprehensive, high resolution, process-based quantification of virtual land and water flows and footprints in present and future times. The agricultural and hydrosphere model LPJmL – which I will shortly present in the next paragraphs – offered an optimal tool to tackle this task.

The Lund-Potsdam-Jena model (LPJ) is a dynamic global vegetation model that was developed based on the equilibrium model BIOME3 in the late nineties (Sitch, 2000; Sitch et al., 2003). It was then further developed to represent agriculture by Bondeau et al. (2007), originating the Lund-Potsdam-Jena managed Land model (LPJmL). Since then LPJmL was developed and improved in many areas, including the coupling between the bio- and the hydrosphere (Gerten et al., 2004) and the incorporation of a river routing scheme, reservoirs and dams (Rost et al., 2008; Biemans et al., 2011).

LPJmL uses climate, CO_2 concentrations, land use patterns and soil structure as inputs to simulate sowing dates, photosynthesis, phenology, maturity, production and carbon stocks of 11 crop functional types, an additional commodity group called "other crops" and managed grasslands. Also carbon and water fluxes between different compartments (atmosphere, plants, soil) are modeled.

LPJmL gives hence a unique opportunity to overcome some of the shortcomings explained above and close some of the research gaps described, advancing the field as will be explained in the next section.

1.3 Objectives

While giving an integral picture of the spatial patters and dimensions of virtual resources flows, this PhD thesis will advance the field through the following specific contributions:

1) To analyze for each country how efficient agriculture uses land and water today and how climate change is going to affect these productivities (Chapter 2 and 3), including:
   - Spatially and temporally explicit assessment of virtual water contents and agricultural yields for the world major crops.
   - Simulation of the effects of climate change and CO_2 fertilization on virtual water contents and agricultural yields.
   - Analysis of the determining factors of the spatial patterns of virtual water contents for the current time and under climate change and CO_2 fertilization.

2) On the basis of high resolution water and land productivities, to estimate the international virtual land and water flows, the water footprints of each country and the water and land saved/lost through international trade (Chapter 4), including:
   - The explicit differentiation of the green and blue components in virtual water flows and footprints in order to assess the contribution of green and blue water to the production of agricultural goods for exports and for domestic consumption.
   - The explicit differentiation of the internal and external components of green and blue water footprints.
   - The first analysis of international virtual land flows and land savings.

3) On the basis of virtual land and water saved/lost, to analyze the dependence of each country on international trade, accounting for future population change, possible improvements in agricultural management and potentials for cropland expansion and water consumption increase (Chapter 5), including:
   - The comparison of water and land needed for self-sufficiency with water and land availabilities, for the current time, and under improved agricultural management and population change.
   - The calculation of the number of people dependent on *ex situ* land and water resources for the present time, and also for different scenarios of agricultural productivity.

These three main objectives will be complemented by a comprehensive evaluation and validation of simulation results and comparison with former estimates presented in each chapter.

Furthermore, for answering these questions, following steps will be performed:

- The compilation of a land use dataset from 1700 to current time, for the major agricultural commodities worldwide, differentiating between rainfed and irrigated areas.
- The compilation of a global dataset of productive land at country scale.
- Improvement in crop parameterization of the LPJmL model.
- Improvement of the representation of agricultural management in LPJmL through a calibration procedure.
- Coupling of LPJmL results with bilateral trade data.
- The simulation of water availabilities in LPJmL at country scale.
- The definition of scenarios of future agricultural productivities and their representation in LPJmL in order to simulate yields, production, virtual water contents and water consumption under improved agricultural productivities.

Finally, the general conclusions of this PhD thesis will be exposed in Chapter 6, where also the innovative aspects of the work will be highlighted and recommendation for future work will be given.

1.4 Author’s contributions

In the following the contribution of the author in each chapter will be highlighted:

Chapter 2: I collected and prepared the data needed for the compilation of the new land use dataset for LPJmL and implemented it in the model. I also made the literature review, designed the calibration process in LPJmL, adjusted the parametrization for all crops in LPJmL, made all model runs, plotted the maps and graphics, interpreted the results, compared the results with other estimates and wrote the manuscript. Stefanie Rost participated in the discussion on how to represent agricultural management in LPJmL, provided help with technical difficulties, introduced M. Fader to the model functioning and helped in the programming for the compilation of the land use dataset. Christoph Müller implemented the calibration process in LPJmL and revised the manuscript. Alberte Bondeau participated in the discussions on how to represent agricultural management in LPJmL. Dieter Gerten participated in all discussions and contributed to the manuscript with helpful comments.

Chapter 3: With the model improvements shown in Chapter 2, I had set the basis for the yield calculations exposed in Chapter 3. I also participated in the discussions on the concepts to be included, the structure of the manuscript, the runs to be made and climate scenarios to be used. Additionally, I wrote the abstract, the introduction (both not published) and had the idea of looking at scenarios' agreement, and thus calculated and plotted it (in Fig. 3.3). Christoph Müller made the model runs and wrote the published manuscript. Alberte Bondeau, Alexander Popp, Katharina Waha contributed to the graphics, the interpretation and the manuscript.

Chapter 4: I designed the methodology, made the literature review, performed all model runs, programmed all post-processing scripts concerning the coupling of trade and model data, plotted the maps and graphics, interpreted the results, compared the results with other estimates and wrote the manuscript. Dieter Gerten participated in all discussions and contributed to the manuscript with helpful comments. Markus Thammer prepared the trade data. Jens Heinke, Hermann Lotze-Campen, Wolfgang Lucht and Wolfgang Cramer participated in discussions.

Chapter 5: Based on the study on virtual water and land flows, I had the idea of quantifying dependence on external resources. I also made the literature review, designed the methodology, implemented higher and potentials agricultural productivities in LPJmL, made all model runs, programmed all post-processing scripts concerning the coupling of trade, model, population, water and land availability data, plotted the maps and graphics, interpreted the results, compared the results with other estimates and wrote the manuscript. Dieter Gerten participated in all discussions and contributed to the manuscript with helpful comments. Michael Krause prepared and harmonized a part of the dataset on available land. Wolfgang Lucht and Wolfgang Cramer participated in discussions and revised the manuscript.

The conclusions and outlook exposed in **Chapter 6** were conceived and written by me.

In my PhD time I was also involved in the preparation of two other publications: "Global water availability and requirements for future food production" (Gerten et al., 2011) and "Measuring agricultural land-use intensity" Dietrich et al. (submitted) (please see section "Publications" for a list of my publications).

Chapter 2

Virtual water content of temperate cereals and maize: Present and potential future patterns[1]

Marianela Fader, Stefanie Rost, Christoph Müller, Alberte Bondeau, and Dieter Gerten

Abstract

Knowledge of the virtual water content (VWC) of crops and especially its possible future developments is helpful for improvements in water productivity and water management, which are necessary at global scale due to rising demand for food, the necessity to ease present and future water scarcity, and the reduction of poverty. Using a dynamic global vegetation and water balance model (LPJmL), this study quantifies the VWC of two of the most important crop types worldwide, temperate cereals and maize, at high spatial resolution (0.5°). We analyzed present conditions (1999–2003) and also, for the first time, for scenarios of future climate and increasing atmospheric CO_2 concentrations (2041–2070; HadCM3, ECHAM5 and CCSM3 climate models, A2 emissions scenario). VWC presently differs significantly among regions: highest values are common in large parts of Africa (>2 $m^3\ kg^{-1}$), and lowest values were found e.g. for Central Europe (<0.5 $m^3\ kg^{-1}$), indicating that water productivity of crops is much higher in the latter region. The regional patterns of VWC result from complex and interactive processes; the dominant factor is the crop yield level (high VWC values occur most frequently in regions with low yields). Climate change and rising atmospheric CO_2 concentration will have non-uniform effects on crop yields and evapotranspiration. Worldwide VWC patterns will change significantly, with a pronounced regional pattern that reflects primarily the changes in yields as driven mainly by regionally decreasing precipitation, increasing temperature and increasing atmospheric CO_2 concentration. Although globally the water productivity is projected to increase, many regions—including parts of the US, East and Mediterranean Europe, South Africa, Argentina,

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Australia and South East Asia—are projected to become less water efficient (higher VWC) for at least one of the crop types. CO_2 fertilisation was simulated to generally reduce VWC, though realisation of this effect in the field will depend, for example, on the intensity of nutrient management in the future. The potentially adverse future changes in VWC found here pose a challenge to water management efforts and eventually global trade policies.

2.1 Introduction

Accessible fresh water is scarce and an essential input for many societal, economic and natural systems. Only 1% of the global water volume is accessible freshwater (Wallace and Batchelor, 1997), and it is likely that this quantity will decrease in many regions under future climate change, e.g. through more frequent and more pronounced droughts and through reduced inflow from glaciers (Bates et al., 2008). The current high water consumption of agriculture, the rising demand for food, the necessity to ease present and future water scarcity as well as increasing trade-offs between different water-uses point to the need for quantifying the present and future virtual water contents—i.e. the amounts of water consumed (evapotranspired) to produce a unit of biomass or yield (see below)—of individual crops. Additionally, reliable virtual water content calculations are the basis for analyses of virtual water trade—the amount of water implicitly traded around the world through trade of agricultural commodities (e.g., Hoekstra and Hung, 2002; de Fraiture et al., 2004; Yang et al., 2006). Postel (1998) suggested that 25% of present grain trade is driven by water scarcity, and this number is likely to increase under climate change (e.g. if droughts will occur more frequently in present export countries) and under demographic change (leading to increased demand for food and potentially increased virtual water trade).

Producing food involves consumption of large amounts of freshwater in the processes of plant transpiration, interception loss from vegetation canopies, soil evaporation and channel evaporation in irrigated systems. Agriculture accounts for about 70% of human water withdrawals (Molden et al., 2007b), and recent estimates indicate that up to 8800 km^3 yr^{-1} are consumed in global rainfed and irrigated crop systems (Rost et al., 2008, and references therein). For wheat alone, between 400 and 2000 L of water per kg of grain are being consumed globally (Molden et al., 2007b).

The specific water requirements of individual crops can be quantified by the crop water productivity (CWP, typically in kg m^{-3})—which is the ratio between produced crop yield and the amount of water consumed (evapotranspired) for that production (Bessembinder et al., 2005)—or the inverse ratio, the virtual water content (VWC, typically expressed in m^3 kg^{-1}). VWC and CWP differ not only among crop types, but also among regions for an individual crop. For example, Zwart and Bastiaanssen (2004) found that with 1 m^3 of water it is possible to produce higher wheat yields in Wangtong (China) or Grand Valley (USA) than in Meknes (Morocco) or in Tel Hadya (Syria). Moreover, the amounts of water consumed in agricultural production differ between irrigated and rainfed systems (Liu et al., 2007).

Since crop yields and evapotranspiration—thus VWC—are determined to a large extent by climatic conditions, future changes in climate are likely to affect VWC in multiple and non-linear ways. For example, an increase in temperature will increase evapotranspiration, but it could both increase and decrease crop yields, leading to decreasing or increasing VWC. Concurrent changes in precipitation and resulting changes in soil moisture may either amplify or dampen the temperature response. In addition, rising atmospheric CO_2 concentration will affect both crop transpiration (which tends to decrease due to lower stomatal aperture) and yield (which tends to increase due to higher water productivity and/or higher carbon assimilation rates) (e.g., Tubiello and Ewert, 2002; Kimball et al., 2002; Ainsworth and Long, 2005; Gerten et al., 2007). Potential changes in VWC under conditions of future climate and atmospheric CO_2 change have not yet been investigated at the global scale.

In the present study, VWC was computed in a process-based and dynamic manner using a well-established model of the global biosphere and agrosphere, LPJmL (Lund-Potsdam-Jena managed Land; Bondeau et al., 2007; Rost et al., 2008). We quantified, geographically explicitly, the VWC of two of the world's major crop types—temperate cereals and maize—for the period 1999–2003, based on a recently developed land-use dataset that provides spatially explicit information on crop-specific irrigated and rainfed areas (Portmann et al., 2010). Furthermore, we here present the first quantitative assessment of future changes in VWC under climate change projections from three different climate models and one emissions scenario. This allows for identifying hotspots regions of change in VWC and main drivers of change.

2.2 Modelling approach and data

2.2.1 The LPJmL model

LPJmL is a process-based ecosystem model which simulates the growth, production and phenology of nine plant functional types (representing natural vegetation at the level of biomes; Sitch et al., 2003) and of 11 crop functional types (CFTs) (Bondeau et al., 2007). Carbon fluxes (gross primary production, auto- and heterotrophic respiration) and pools (in leaves, sapwood, heartwood, storage organs, roots, litter and soil) as well as water fluxes (interception, evaporation, transpiration, soil moisture, snowmelt, runoff, discharge) are modelled accounting explicitly for the dynamics of natural and agricultural vegetation. For example, carbon and water fluxes are directly linked to vegetation patterns and dynamics through the linkage of transpiration, photosynthesis and plant water stress. Additionally, rising atmospheric CO_2 concentration directly affects transpiration and biomass production through physiological and structural plant responses (Gerten et al., 2004, 2007). Water requirements and water consumption—and thereby VWC—of irrigated and rainfed crops can be distinguished. The phenology (sowing and harvest dates) of the different CFTs is simulated dynamically based on CFT-specific parameters, past climate experience and daily soil moisture, allowing for adaptation of varieties and growing periods to climate change (see ''2.2.3 Calculation of crop yields" and Bondeau et al., 2007, for details). All processes are modelled at a daily resolution and on a global 0.5° grid.

Annual fractions of a grid cell covered by an individual CFT (either rainfed or irrigated), and the historic evolution of these fractions, are prescribed using external data (see ''2.6.1 Implementation and description of the new land-use dataset" for a detailed description of these datasets). The suitability of the model (and its predecessor LPJ that did not include cropland) for vegetation, crop and water studies has been demonstrated before by validating simulated phenology and yields (Bondeau et al., 2007), river discharge (Gerten et al., 2004; Biemans et al., 2009), soil moisture (Wagner et al., 2003), evapotranspiration (Sitch et al., 2003; Gerten et al., 2004) and irrigation water requirements (Rost et al., 2008).

2.2.2 Model setup and simulations

To represent past and present conditions, LPJmL was forced for the period 1901–2003 by monthly values of air temperature, precipitation amounts, number of wet days, and cloud cover taken from an enhanced CRU TS2.1 climate database (Österle et al., 2003), disaggregated to daily values as described by Gerten et al. (2004). In a spin-up simulation, the climate of the years 1901–

1930 was repeated 30 times prior to the transient period studied here, in order to bring the distribution of natural vegetation and the carbon pools into equilibrium. Soil characteristics and annual atmospheric CO_2 concentrations were prescribed according to Keeling and Whorf (2003).

Climate projections of three GCMs were used for transient simulations up to the year 2070: ECHAM5 (Jungclaus et al., 2006), HadCM3 (Cox et al., 1999), and CCSM3 (Collins et al., 2006). The bias correction or direct forcing method (Lenderink et al., 2007) was applied for the construction of future climate: in the first instance, monthly mean temperatures, precipitation and cloudiness were downscaled to 0.5° resolution by bi-linear interpolation for each year. Subsequently, the anomalies between the monthly averages of the GCMs and the observed climate for the period 1961–1990, were calculated as absolute monthly mean difference for temperature and as ratio of monthly means for precipitation and cloudiness. These anomalies were used as correction factors for each monthly GCM value (additive for temperature, multiplicative for precipitation and cloudiness). Since there was no information about the number of wet days in the future, these were kept constant after 2003 at the 30-year average of 1971–2000.

To account for climate-change-only effects as well as for the combined effects of climate change and CO_2 fertilisation, we performed two simulations, one assuming gradual CO_2 increase according to the IPCC-SRES A2 scenario (reaching 635 ppm in 2070) and one with CO_2 concentration held constant at the level of 2000 (369.5 ppm). In both cases the land-use pattern of 2000 was held constant for the future. The projected future changes in average annual VWC were analysed as differences between the period 2041–2070 and the period 1971–2000.

2.2.3 Calculation of crop yields

Table 2.1 shows the relevant LPJmL parameters for the two CFTs under study here; in the following, only a brief description of the simulation of crop growth and related biogeochemical processes is given—more detail is provided by Bondeau et al. (2007).

The start of the growing period is calculated depending on climate (20-yr average of the day when temperature crosses a variety-specific threshold for temperate cereals, and a combination of the temperature-based start of the growing season with actual water availability for maize). Photosynthesis is modelled by means of a generalised Farquhar model (Collatz et al., 1992), and this is done slightly differently for C3 and C4 crops to account for their different photosynthetic pathways (e.g., C4 plants are characterized by a faster carbon fixation, which allows for shorter stomata opening times and therefore less water loss by transpiration; see Haxeltine and Prentice, 1996a,b, and Sitch et al., 2003, for details). Crop phenology is modelled based on the heat unit theory: when daily mean temperatures above a determined base temperature accumulate to a given value of growing degree days, maturity is reached. The daily assimilation of carbon from the atmosphere is allocated to the above mentioned pools, depending on the phenological stage and adjusted in the case of water stress. A harvest index determines the above-ground biomass fraction allocated to the storage organs at harvest; its minimum (in the case of severe water stress) is determined by a minimum harvest index, HI_{min} (see Table 2.1).

The harvest day is determined by maturity or by exceedance of the prescribed maximum number of growing days. All CFTs are assumed to be harvested within one year's time.

The simulated carbon pool for storage organs were converted to dry matter yield as described in Eq. (1).

$$Y_{CFT} = \frac{H_{CFT}}{0.45} * 10^2 \qquad (1)$$

where Y_{CFT} is the dry matter yield (t DM

Table 2.1: Most relevant LPJmL parameters for temperate cereals (wheat) and maize.

CFT	Sowing date	Base temperature (°C)	Phenological heat units (degree-days)	Maximum leaf area index (LAI_{max})	Optimum harvest index at harvest	Minimum harvest index at harvest	Maximum number of growing days
Temperate cereals (wheat, barley, rye)	Function of temperature and temperature memory	0	1000–2877, Depending on sowing date	1–7 On country-level	$0.5 * 0.8 + \frac{0.2}{6} * (LAI_{max} - 1)$	0.2	330
Maize	Function of temperature and soil water content	5–15	1600	1–7 On country-level	$0.5 * 0.8 + \frac{0.2}{6} * (LAI_{max} - 1)$	0.3	240

ha^{-1}), H_{CFT} is the harvested carbon (g C m^{-2}) of a CFT, and 10^2 converts from (g DM m^{-2}) to (t DM ha^{-1}).

In the improved LPJmL version 3.3 used in this study, management intensity—i.e. the degree and frequency of crop production control and input application (fertiliser, technology, labour, weed and diseases control, etc.)—is represented by three parameters: LAI_{max}, HI_{max}, and α–a. The country-specific LAI_{max} parameter (with values between 1 and 7 m^2 m^{-2}, see below) describes the maximal attainable leaf area index (LAI) of a crop. The LAI is the ratio of total upper leaf surface of vegetation divided by the surface area of the land on which it grows, representing the density of individual plants, their average productivity and, thus, the management intensity. The maximal harvest index (HI_{max}), i.e. the above-ground biomass fraction allocated to the storage organs at harvest in the absence of water stress, is directly coupled to this management intensity, assuming that high-yielding crop varieties grow on intensively managed fields. If, for example, management intensity is low (LAI_{max} = 1), HI_{max} is reduced by 20%. The α–a parameter scales leaf-level biomass production to stand level (a stand is the fraction of a grid cell characterised by a common climate, soil and land-use), also following LAI_{max}. The assumption is that intensively managed crop stands (LAI_{max} = 7) have little or no areas with reduced productivity (α–a = 1.0) due e.g. to poor soil conditions or pests and diseases, while such areas are more common in extensively managed crop stands (LAI_{max} = 1; α–a = 0.4). The used ranges of LAI_{max} and HI_{max} are based on empirical knowledge from many different sources (see e.g. Krysanova and Wechsung, 2000; Neitsch et al., 2005; Bavec and Bavec, 2002). The range of α–a (0.4–1) is based on the global average α–a value for natural vegetation in LPJmL (0.5), which was derived by Haxeltine and Prentice (1996a,b) after data from Landsberg (1986). This scaling factor represents the reduction in the utilisation efficiency of photosynthetically active radiation (PAR) through leaf characteristics (e.g. texture, sun exposition) and other processes, such as herbivores and symbiotic relationships. We thus assume that there is optimal PAR utilisation in highly managed fields.

Due to the lack of global data and the necessarily simplified treatment of agricultural management in the current model version, the management intensities were calibrated by sequentially varying for every country the CFT-specific LAI_{max} parameter between 1 and 7 (in intervals of 1), and with it the coupled α–a (0.4–1.0 in intervals of 0.1) and HI_{max} parameters (100–80% of the CFT-specific HI_{max}, in intervals of 3.3%). Since a correctly simulated yield is essential for computing VWC values, we here use the management intensities that result in the best approximation of the 1999–2003 national yields of wheat (as a proxy for temperate cereals) and of maize (for food) as reported by FAOSTAT (2009). We chose this period because the land-use input to LPJmL has been compiled for around the year 2000 (see Appendix "2.6.1 Implementation and description of the new land-use dataset" for details). The thus determined country-level and CFT-specific management classes were assigned to each grid cell within a country (see Appendix "2.6.2 Agricultural management intensity" for LAI_{max} maps). We did not derive different parameter values for irrigated and rainfed areas because these are not separated by FAO.

We performed a sensitivity analysis to test the response of VWC and its future changes to systematic increases and decreases of LAI_{max}. We varied values of LAI_{max} within a limited range only (±2), since it makes no sense to deviate too much from the default value chosen to represent best the current management. As expected, yields increase (decrease) globally with increasing (decreasing) LAI_{max}. Total evapotranspiration (E) is much less sensitive due to opposite responses of evaporation and transpiration in response to LAI change. As a net result, the VWC of both CFTs increases (decreases) with decreasing (increasing) LAI_{max}. Changes in VWC under climate change would also be affected by such a change in LAI_{max}, which is reasonable, since the response to changing climate and atmospheric CO_2 concentrations is non-linear and percent change rates thus depend strongly on the initial values.

In the simulations of future VWC, we assumed static management conditions (with the exception of climate-adapted sowing dates and variety selection), i.e., LAI_{max} was held constant for the future.

Since the reported yields are expressed in hg ha^{-1} fresh matter, we converted them to dry matter values by means of crop-specific factors (0.88 for maize and wheat) following Wirsenius (2000). To measure the agreement between simulated (LPJ in Eq. (2)) and reported yields (FAO), we calculated the Willmott coefficient of agreement W_{CFT} (Willmott, 1982) for each CFT and each country i:

$$W_{CFT} = 1 - \frac{\sum_{i=1}^{n}(FAO_i - LPJ_i)^2}{\sum_{i=1}^{n}\left(\left|LPJ_i - \overline{FAO}\right| + \left|FAO_i - \overline{FAO}\right|\right)^2}$$

(2)

where FAO refers to the average of reported yields over all countries. A value of 1 in W_{CFT} indicates a perfect match, while a value of 0 indicates complete disagreement.

2.2.4 Evaluation of simulated crop yields

The yields of both crops can be reproduced very well at the global scale after the management calibration (Fig. 2.1a and b). Wheat yield (W_{CFT} = 0.96) is underestimated for the UK and Germany, possibly because of an erroneous temporal distribution of simulated summer and winter wheat. Maize yield (W_{CFT} = 0.87) is also underestimated in some countries such as the US and Canada. One probable reason for this is the widespread use of hybrid species with even higher harvest indexes than those assumed here. It has to be noted that most FAO yield data used in this study are ‘‘estimates and calculated data” (FAOSTAT, 2009) and that certain countries have missing values for some years or some crops, due to missing reports or due to changes in country classification within the FAO as e.g. for Montenegro (in these cases, we assumed an LAI_{max} of 5).

2.2.5 Computation of virtual water content (VWC)

In this study, the VWC (m^3 kg DM^{-1}) of a CFT in each grid cell (p) is defined as follows:

$$VWC_{CFT\_p} = \frac{10 * E_{CFT\_p}}{Y_{CFT\_p}} \qquad (3)$$

where Y is the yield (kg DM ha^{-1} yr^{-1}) and E is the evapotranspiration (mm yr^{-1}) computed following the Priestley–Taylor method as the sum of soil evaporation (E_S), interception loss (E_I) and plant transpiration (E_T) over the growing period (sowing date to harvest). The factor 10 converts units from mm to m^3 ha^{-1}. Accounting for E rather than only E_T has the advantage of considering the total water depletion—i.e., process and non-process water depletion (Molden, 1997)—which is more realistic since E_S and E_I unavoidably occur in synchrony with E_T and since the processes are interlinked.

Irrigation is modelled to occur if soil moisture falls below 90% of the water holding capacity and the CFT thus experiences water limitation. The irrigation water requirement is determined from the difference between atmospheric demand for ET and soil water supply; this amount of water plus country-specific water losses through ineffective irrigation systems are assumed to be available from rivers, lakes and aquifers (details in Rost et al., 2008). E_I is simulated as:

$$E_I = E_q * \alpha * f_{wet} * f_v \quad (4)$$

where E_q (mm d^{-1}) is the daily equilibrium evapotranspiration which depends on net radiation and temperature, α is the Priestley-Taylor coefficient (=1.32), f_{wet} is the fraction of the day during which the canopy is wet (dependent on canopy storage capacity and potential evapotranspiration), and f_v is the cell fraction covered by a CFT under consideration of seasonal phenology (Gerten et al., 2004).

E_T (mm d^{-1}) is calculated as:

$$E_T = \min(S, D) * f_v \quad (5)$$

where S is the supply of soil moisture constrained by plant hydraulic traits weighted with the fraction of roots in each soil layer (f_R), and D is the atmospheric demand for transpiration (both in mm d^{-1}), estimated as follows:

$$S = E_{max} * f_R * W_r \quad (6)$$

where E_{max} is the plants' maximum transpiration rate at soil saturation (8 mm d^{-1}) and W_r is the relative soil moisture available for plants, depending on soil texture. D is calculated as:

$$D = \frac{(1 - f_{wet}) * E_q * \alpha_m}{1 + \frac{g_m}{g_{pot}}} \quad (7)$$

where α_m is a maximum Priestley-Taylor coefficient (1.391), g_m is a scaling conductance (3.26 mm s^{-1}), and g_{pot} [mm s^{-1}] is the potential, not water limited canopy conductance of carbon and water depending on CFT-specific net photosynthesis and ambient and intercellular CO_2 concentration (Gerten et al., 2007).

E_S is given by

$$E_S[\text{mm d}^{-1}] = E_q * \alpha * (W_{r20})^2 * (1 - f_v) \quad (8)$$

where W_{r20} is the relative moisture of the upper 20 cm of the soil.

From the computed grid cell values of irrigated and rainfed VWC, area-weighted country averages were derived considering the different contributions of irrigated and rainfed areas.

The fraction of E that stems directly from precipitation—which is the case in rainfed regions and also in irrigated regions to the extent that precipitation water stored in the soil contributes to E—is the ‘‘green water” resource, while in irrigated areas part of E stems from ‘‘blue water” taken from rivers, lakes and aquifers for irrigation (Rost et al., 2008; Rockström et al., 2009). While it is possible to calculate the individual contributions of green and blue water to total evapotranspiration on irrigated land, their contributions to the VWC of irrigated CFTs cannot be clearly separated, because if blue water is added, crop yields will increase disproportionally compared to E, such that the blue (and green) VWC cannot be derived linearly from the blue (green) E. If an additional simulation was performed in which irrigation was omitted (so as to estimate the isolated green water contribution to Y, E and VWC), the CFTs would not grow at all in many regions (i.e. the green water fraction of E would be zero), such that the difference between the full model run and that model run would in mostly overestimate the contribution of blue water to Y and VWC. Therefore, we only computed a ratio (BTG) between the blue and green water fractions of E and its future changes, as follows:

$$BTG_{CFT\_P} = \frac{BWC_{CFT\_P}}{GWC_{CFT\_P}} \quad (9)$$

where BWC is the blue water consumption and GWC is the green water.

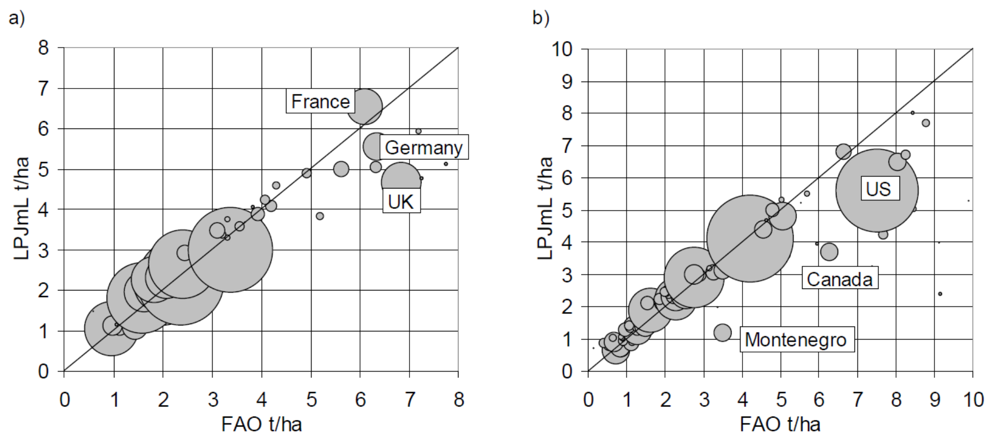


Figure 2.1: Scatterplot of LPJmL-simulated yields (averages over 1999–2003) versus reported yields (t DM ha^{-1}) (a. wheat, b. maize). The bubbles indicate the relative size of the harvested area in the respective country according to FAO.

consumption for each grid cell (P) and each CFT, for irrigated areas.

2.3 Results

2.3.1 Present-time VWC

Analysis of spatial patterns

Fig. 2.2 shows the global patterns of irrigated and rainfed VWC for maize and temperate cereals, averaged over 1999–2003. Generally, the lowest values (country means around 0.3 m^3 kg^{-1} for temperate cereals, 0.5 m^3 kg^{-1} for maize) were computed for Central and western Europe, followed by East Europe, the eastern US and south-eastern China. The highest values (in the order of 5 m^3 kg^{-1} for temperate cereals and 10 m^3 kg^{-1} for maize at country-level) were found for the Middle East, Africa and some South American regions. The values depend, however, on the crop considered and whether or not it is irrigated (Fig. 2.2; see also ‘‘Differences between irrigated and rainfed conditions, and between CFTs”).

The spatial heterogeneity of LPJmL-simulated VWC can only be explained by a combination of different factors. The dominant factor in the case of rainfed maize—which we analyse exemplarily here—appears to be the yield level (compare Eq. (3)), as almost all grid cells with VWC >3 m^3 kg^{-1} show yields <2 t ha^{-1}, i.e. high values of VWC are basically constrained to low-yielding regions (data not shown). Fig. 2.3a shows the relation between E and VWC for rainfed maize and yields >2 t ha^{-1}. It clearly shows that in regions where E is very low (water- and/or energy-limited) high yields are still possible in combination with low VWC. This indicates that E is dominated by productive E_T, while E_S is low (see also e.g. Rockström and Barron, 2007). This case can be found in industrialised countries (e.g. US, Canada, Netherlands, Germany, France, Belgium), for highly managed croplands in developing countries as well as in economies in transition (e.g. Thailand, South Korea, Poland, China). At high E level we do not find VWC values lower than approx. 1 m^3 kg^{-1} as there are no yields >9 t ha^{-1}. For low yield levels (<2 t ha^{-1}) a wide range of VWC was found (data not shown) and there was a high number of grid cells (~44%) with relative short growing periods (<125 days), low E_{pot} over the growing period (<400 mm) and high water stress (>0.6, defined as the ratio of actual over potential canopy conductance as computed after Gerten et al., 2007). This means that low yields could be caused by a combination of radiation deficiency and water limitation. This combination is also the most numerous one when looking at VWC values >5 m^3 kg^{-1}. Tropical regions with VWC >5 m^3 kg^{-1} and

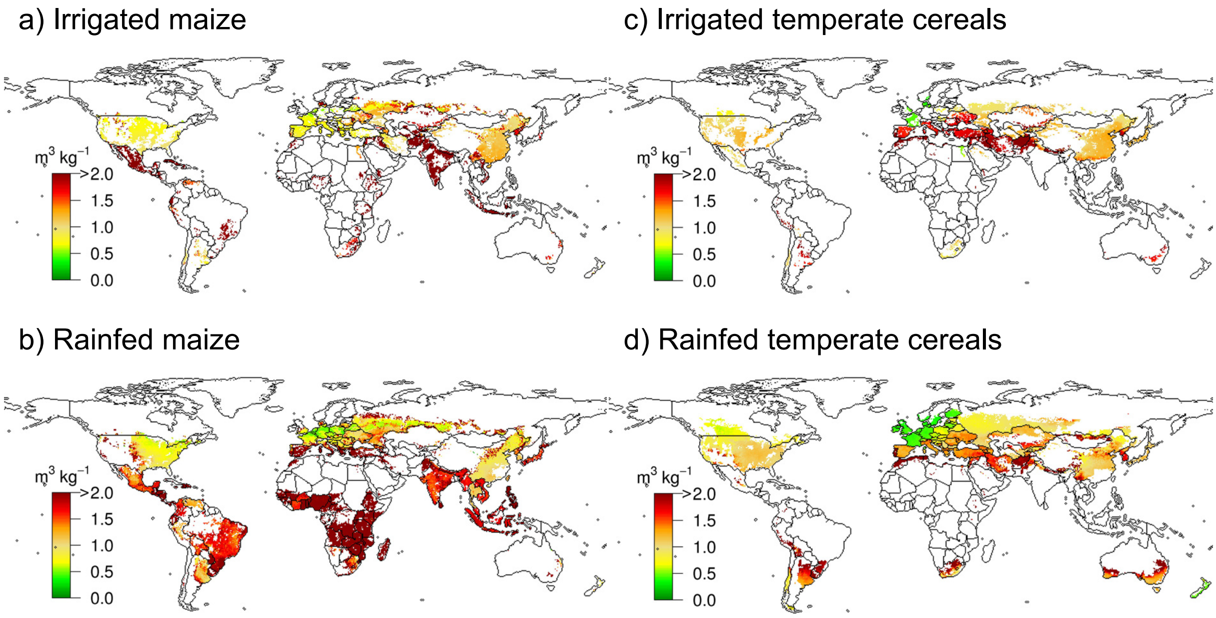


Figure 2.2: Global maps of LPJmL-simulated VWC (m^3 kg^{-1}, 1999–2003 averages) of irrigated and rainfed maize and temperate cereals.

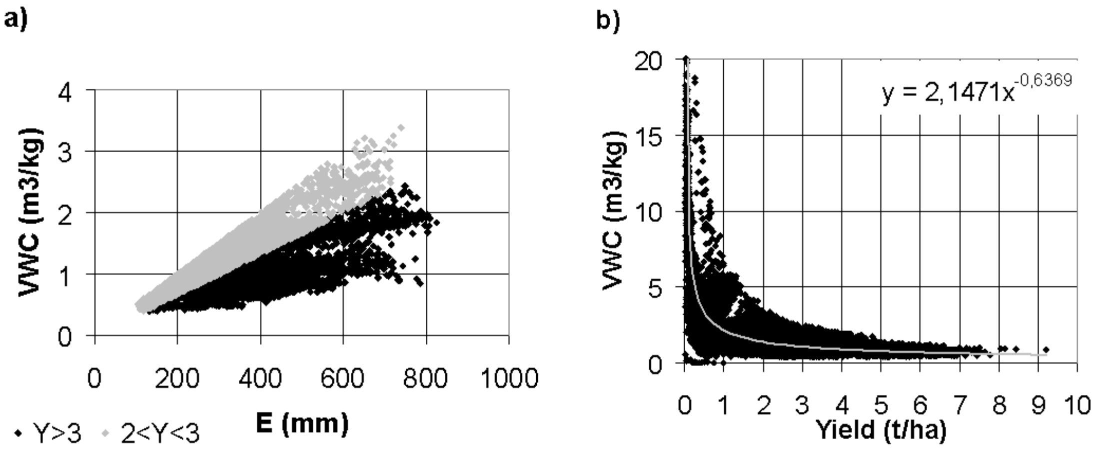


Figure 2.3: Scatterplots of LPJmL simulations for rainfed maize (averages over 1999–2003). a. Evapotranspiration E (mm) and VWC (m^3 kg^{-1}) for grid cells with yields >2 t ha^{-1}. b. Yields (t DM ha^{-1}) and VWC (m^3 kg DM^{-1}). Every point represents one grid cell.

yields <2 t ha^{-1} have however mainly a combination of high E (>200 mm), high E_{pot} (>400 mm) and are generally connected to long growing periods (>125 days) and high water stress (>0.6).

Fig. 2.3b shows the relation between rainfed maize yields and VWC. The showed fitting function presents at almost each point an elasticity >1, indicating that VWC is yield elastic, i.e. sensitive to yield changes. The function flattens with increasing yields, suggesting that high yields are always accompanied by efficient water-use, i.e. low VWC. On a low yield level, however, there is a broad range of possible VWC. This indicates that low VWC values cannot be explained by yield level. The general shape of the curve applies for each region but the curvature is different (data not shown). These results are in very good agreement with Rockström et al. (2007).

Differences between irrigated and rainfed conditions, and between CFTs

The differences between rainfed and irrigated VWC for all grid cells where both of these cases occur are non-uniform (see Fig. 2.2). For maize, VWC is higher for rainfed than for irrigated production systems in e.g. the Mediterranean region, since in our simulation the increase of yields through irrigation overcompensates the increase of E there. However, the opposite appears to be true for other regions such as Brazil, Mexico and parts of India and China, where irrigation increases E disproportionally compared to the yields, causing higher VWC. For temperate cereals, VWC is lower under irrigated conditions than under rainfed conditions for regions such as South Africa and Egypt, which agrees with Liu et al's. (2007) finding for wheat. The reverse was found, however, for the Mediterranean region, East Europe and the Middle East, again because the increase of E overcompensates the yield increase through irrigation.

A direct comparison of VWC for temperate cereals and maize within grid cells indicates that in Argentina and in parts of East Europe more water per kg rainfed temperate cereals are needed than per kilogram rainfed maize. The reverse is true for western Europe, the Mediterranean region and Japan. These patterns are probably linked to the combination of different water-use efficiencies (wheat is a C3 crop while maize is a C4 crop) and different management intensities (e.g. in Argentina maize is frequently intensively managed while many wheat areas are extensively managed).

Comparison with earlier estimates

Fig. 2.4a and b show a comparison of our CWP values with measured data from several irrigated locations around the world compiled by Zwart and Bastiaanssen (2004) and with respective results from the GEPIC global crop growth model (Liu, 2009) for maize (a) and temperate cereals (b). The plots demonstrate that both models underestimate the CWP of temperate cereals and that LPJmL underestimates also the CWP of maize. Fig. 2.4c shows that the LPJmL-simulated VWC values are also in good agreement with country-level estimations by Hoekstra and Chapagain (2007a).

Table 2.2: VWC and CWP comparison with earlier estimates for 1999–2003. Note that the reciprocal value of a weighted average is not equal to the weighted average of reciprocal values; this is the reason why 1/VWC is not equal to CWP.

VWC (m^3 kg^{-1})	Maize	Temperate cereals/wheat
LPJmL, this study	2.0	1.4
Hoekstra and Chapagain (2007)	1.3	0.9
Rockström et al. (1999)	1.2	1.5
Molden et al. (2007)	0.3–2.0	0.4–2.0
Gleick (2000)	–	0.9–2.2
CWP (kg m^{-3})	**Maize**	**Temperate cereals/wheat**
LPJmL	0.9	1.0
Zwart and Bastiaanssen (2004)	1.8	1.1
Liu (2009)	1.4	1.0
Molden et al. (2007)	0.3–2.0	0.2–1.2

LPJmL-simulated global 1999–2003 average VWC is 1.4 m^3 kg^{-1} for temperate cereals, and 2.0 m^3 kg^{-1} for maize (Table 2.2). These values are in some cases higher than those calculated by Hoekstra and Chapagain (2007a) and Rockström et al. (1999), but still within the ranges given by Molden et al. (2007b) and Gleick (2000). Analogously, our CWP values are in good agreement with the global mean values for wheat given by Zwart and Bastiaanssen (2004) and Liu (2009) but are lower than their values for maize. Yet, our CWP estimates are within the ranges reported by Molden et al. (2007b), and the spatial patterns of CWP are in very good agreement with those from the GEPIC model (see the Fig. 4 in Liu, 2009). It may be unexpected that the VWC of maize is higher than that of wheat (as C4 plants have higher water-use efficiencies than C3 plants). The reasons are the different geographical distribution of the areas of maize and temperate cereals (maize being located in warm regions with high E_{pot}, which leads to rather high values of VWC), the differences in management

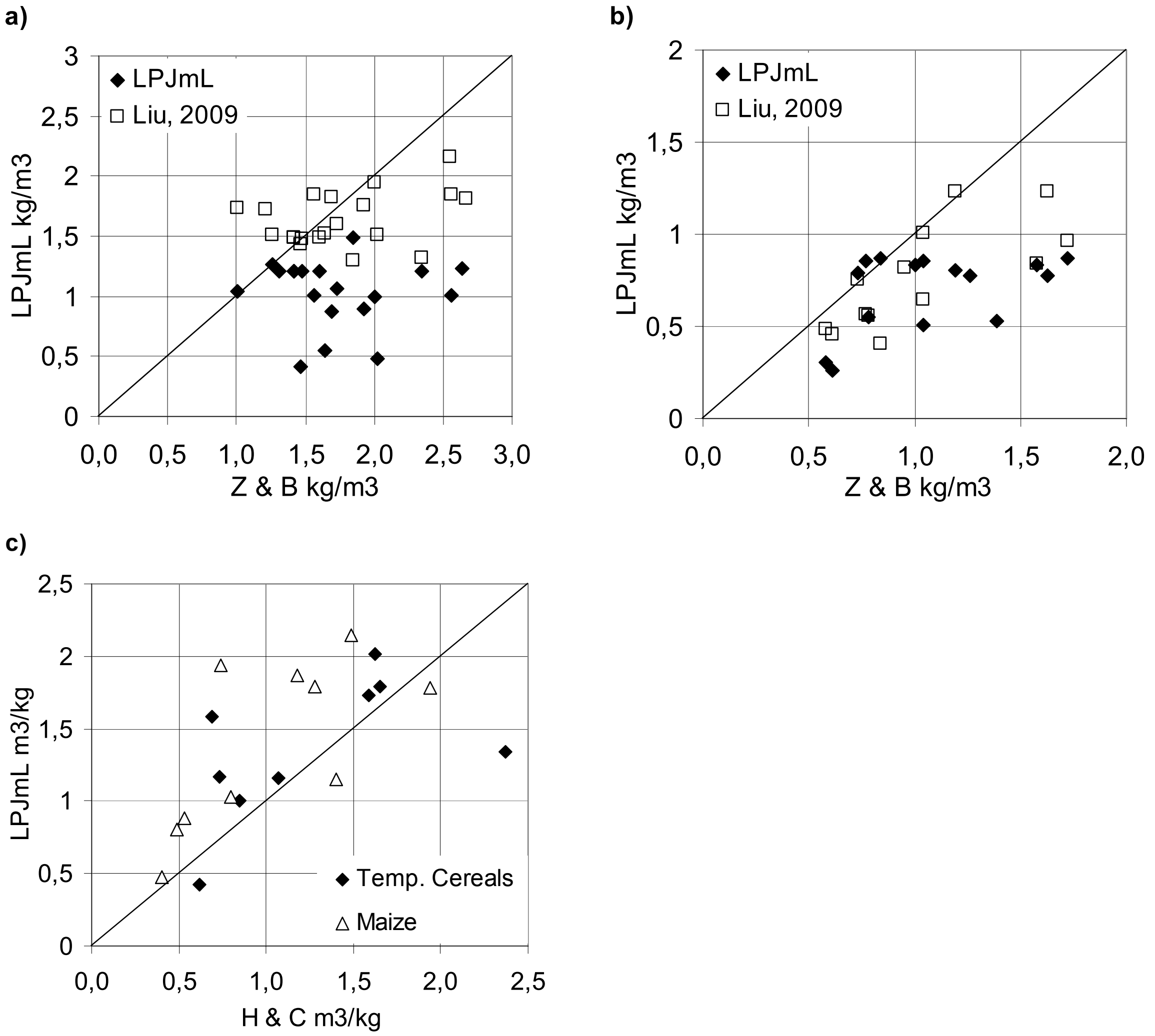


Figure 2.4: Scatterplot of LPJmL simulations (averages over 1999–2003) versus independent data of CWP (kg m^{-3}) (a., b.) and VWC (m^3 kg^{-1}) (c.). Scatterplots in a. and b. represent comparisons for maize and temperate cereals (wheat), respectively. The values of Liu et al. (2009) are for 2000 and for both irrigated and rainfed conditions; the values of Zwart and Bastiaanssen (2004) (Z&B) are for different periods of time and irrigated conditions; the values of LPJmL are from irrigated areas only to make them directly comparable with Z&B. In a. and b. every point represents one grid cell (LPJmL) or one measurement unit (Z&B), in c. every point represent a national average. The country-scale VWC values in c. were taken from Hoekstra and Chapagain (2007a) (H&C).

between these regions, and especially the fact that this study does not consider tropical cereals (as opposed to the other studies in Table 2.2).

2.3.2 Future changes in VWC

Spatial patterns of VWC changes

Fig. 2.5 shows the geographical distribution of changes in VWC under the HadCM3 scenario with constant and dynamic CO_2. Climate change alone (Fig. 2.5a) will increase VWC of both CFTs in many regions, especially in the US, South Africa and Australia for temperate cereals, and in the US, Argentina, Brazil, India, East Europe and the Mediterranean region for maize. However, in some regions VWC decreases due to climate change, especially in some parts of Europe (temperate cereals), tropical Africa as well as northern Europe (maize).

(These decreases outweigh the above mentioned increases in the global mean, see ‘‘Global changes in VWC, E, yields and BTG ratio” and Table 2.3.)

When considering the direct CO_2 effects on crop performance in addition to the climate change effects, VWC decreases in most regions (see Fig. 2.5b). Nonetheless, some regions experience increases in VWC also if CO_2 effects are considered, e.g. the Balkan and India for maize and South Africa for temperate cereals. In these regions the negative effects of climate change exceed the positive effects of CO_2 fertilisation. Moreover, the response of maize to the combined effect of climate and CO_2 fertilisation is mostly weaker (the VWC decrease is lower) compared to temperate cereals. This is because maize as a C4 plant already employs a water efficient carbon fixation mechanism, therefore the water-use efficiency gain through increased CO_2 concentrations is relatively limited.

In Fig. 2.6Ia and IIa it can be seen that changes in VWC are inversely related to climate- and CO_2-driven changes in yields, i.e. decreases in VWC by more than 1 m^3 kg^{-1} are mainly connected to yield increases, and increases in VWC by more than 1 m^3 kg^{-1} are mainly connected to yield decreases. The change in E is hardly decisive for both cases and is driven by the change in E_{pot}. Both results are also true for temperate cereals (not shown).

As a consequence, the factors driving the yield change are indirectly causing the change in VWC. By means of a linear regression analysis, we found that yield increases are explained by up to 20–30% by an increase in the accumulated mean daily temperature (Fig. 2.6Ic and IIc). This relation is especially strong for low increases in the accumulated mean daily temperature (<500°Cd). Examples of this connection are found e.g. in northern Russia for maize and in Mongolia for temperate cereals. Yield decreases can be explained by up to 40–50% by a reduction in accumulated precipitation (see Fig. 2.6Ib and IIb), e.g. across the Balkan for maize and in South Africa for temperate cereals. It is worth noting that both temperature and precipitation are summed over the entire growing period, i.e. an increase in one of them could be caused not only by an absolute increase but also by changes in the length of the growing period. These changes are heterogeneous and in good agreement with other studies (e.g. Kurukulasuriya and Rosenthal, 2003; Wall, 2008): e.g. there is a shortening of the growing period in Argentina for maize and a prolongation in the US and East Europe for temperate cereals, due to a shift from summer to winter varieties.

Under increasing CO_2, some yield reductions due to decreasing precipitation can be compensated by CO_2 fertilisation and improved water productivity (compare Fig. 2.6Ib with Fig. 2.6IIb). The increases in yield in areas with moderate temperature rise (Fig. 2.6Ic and IIc) are stronger under increasing atmospheric CO_2 concentrations and occur also at higher temperature increases (>1000°Cd).

While Fig. 2.5 demonstrates the VWC changes under HadCM3 only, the response pattern somewhat differs for other climate change scenarios. For maize, the climate change effects of the three projections on VWC are very similar in terms of their spatial patterns, but in the case of HadCM3 VWC increases are slightly stronger, especially for the US, Ukraine, Romania and India (see Fig. 2.C in Appendix ‘‘2.6.3 Virtual water content of maize for other GCMs, with constant CO_2”). For the combined climate-CO_2 effects, HadCM3 shows a weaker VWC decrease for the US and also does it show VWC increases for India and the Balkan, where ECHAM5 and CCSM3 show slight decreases. These differences are mainly due to differences in precipitation amounts during the growing season, which affect both E and Y. For temperate cereals, the spatial patterns and relative VWC changes of the three projections considering climate change effects only are very similar. Nevertheless,

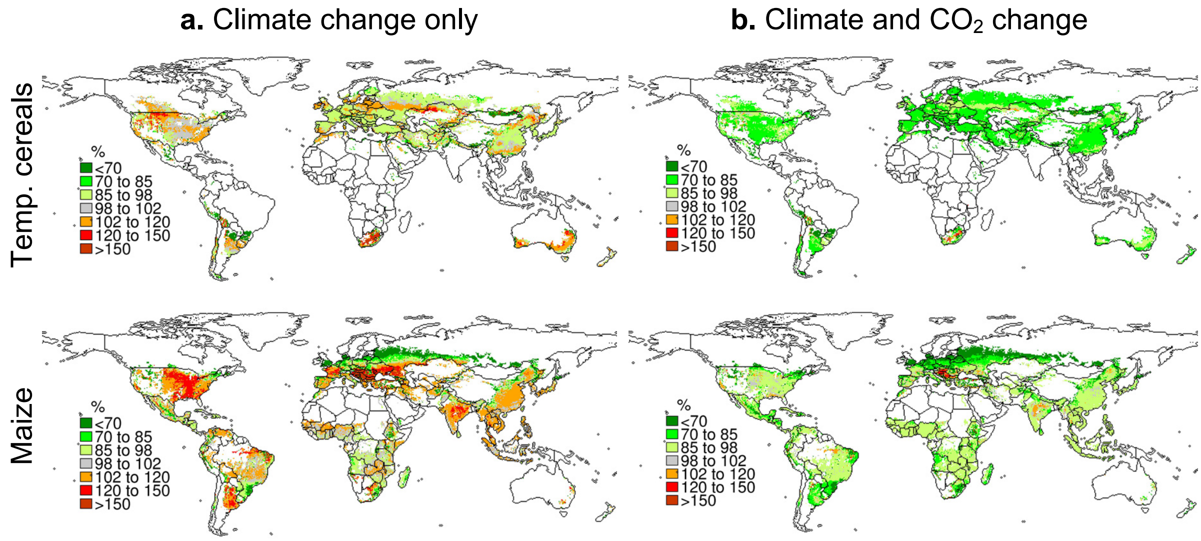


Figure 2.5: Percent changes in VWC of temperate cereals and maize (irrigated and rainfed combined; m^3 kg^{-1}) from 1971–2000 to 2041–2070 under the HadCM3 climate model (SRES A2 emissions scenario), under conditions of climate change only (a.) and under both climate and CO_2 change (b.), respectively. Values <100% (>100%) represent a decrease (increase) in VWC.

Table 2.3: Global changes in VWC, yields (Y), evapotranspiration (E) and the absolute and, in brackets, the percentage ratio between blue and green water consumption (BTG) of temperate cereals and of maize from 1971–2000 (CRU) to 2041–2070. The changes are shown for each of the three GCMs (SRES A2 emissions), for both climate and CO_2 change (dyn. CO_2), and for climate change only (const. CO_2). While the values of ΔBTG refer to irrigated areas only, the other values refer to the average of irrigated and rainfed values.

Climate	Temperate cereals				Maize			
	Δ*Y* (t ha^{-1}) (%)	Δ*E* (m^3 ha^{-1}) (%)	ΔVWC (m^3 kg^{-1}) (%)	ΔBTG ratio (%)	Δ*Y* (t ha^{-1}) (%)	Δ*E* (m^3 ha^{-1}) (%)	ΔVWC (m^3 kg^{-1}) (%)	ΔBTG ratio (%)
CRU	2.4	2564.9	1.45	1.7	3.32	3898.44	1.85	4.0
ECHAM5 dyn. CO_2	0.44 (18)	−199.2 (8)	−0.45 (31)	0.14 (8)	0.27 (8)	−334.12 (8)	−0.35 (19)	2.51 (63)
ECHAM5 const. CO_2	0.03 (1)	−101.04 (4)	−0.22 (15)	0.29 (17)	−0.15 (4)	−209.61 (5)	−0.27 (14)	2.77 (70)
CCSM3 dyn. CO_2	0.57 (24)	−71.63 (3)	−0.43 (30)	−0.09 (5)	0.24 (7)	−306.42 (8)	0 (0)	1.45 (37)
CCSM3 const. CO_2	0.12 (5)	27.92 (1)	−0.19 (13)	0.08 (5)	−0.17 (5)	−171.33 (4)	0.16 (9)	1.74 (44)
HADCm3 dyn. CO_2	0.57 (24)	−65.09 (2)	−0.43 (30)	−0.23 (14)	0 (0)	−426.82 (11)	−0.44 (24)	0.94 (24)
HADCm3 const. CO_2	0.13 (5)	33.19 (1)	−0.19 (13)	−0.09 (5)	−0.48 (14)	−312.98 (8)	−0.18 (10)	1.29 (33)

differences in precipitation and temperature over the growing season cause a stronger VWC increase in Australia under CCSM3. Additionally, the VWC increase in the US is weaker under ECHAM5 than in the other two projections due to a lower accumulated temperature over the growing season. In case of the combined climate and CO_2 effects, joint differences of precipitation and temperature during the growing season lead to slightly lower VWC decreases for the US, Canada, Belarus, Russia and Kazakhstan under the CCSM3 scenario, i.e. the positive CO_2 fertilisation effect is in these cases weaker than under the other two projections (Fig. 2.C, see also Table 2.3).

Global changes in VWC, E, yields and BTG ratio

As an aggregate result of the regional patterns of change, the global average VWC of both crop types is projected to change considerably in the future (Table 2.3). Without CO_2 increase, LPJmL simulates under two out of the three climate change projections improvements (i.e. decreases) in average global VWC by about 0.2 m^3 kg^{-1} (equalling up to 15% for temperate cereals and up to 14% for maize); only under CCSM3 we project a higher global VWC (by 0.16 m^3 kg^{-1}, or 9%). When effects of increasing atmospheric CO_2 concentrations are considered in addition, VWC is generally projected to decrease stronger (see Table 2.3).

The yields of temperate cereals increase under all projections by up to 24% in HadCM3 and CCSM3 with dynamic CO_2—the increases in the scenarios with constant CO_2 being always lower than with dynamic CO_2. E from temperate cereals shows a decrease by up to 8% with dynamic CO_2. In contrast, the climate-only impact on maize yields is always negative, up to 14% under HadCM3. Under dynamic CO_2 conditions, however, yields always increase, by up to 8%. E from maize decreases by 4–11%. This decrease is always higher under the scenarios with dynamic CO_2.

BTG from maize is presently much higher than from temperate cereals, indicating that globally more blue than green water is evapotranspired during the growth of maize (Table 2.3). This reflects that maize is grown in many areas with low precipitation and high atmospheric demand. The sign of the global changes of BTG for temperate cereals disagrees among the different climate change projections: under some GCMs an increase is projected (i.e. an increase of blue water consumption with respect to the green water consumption on irrigated areas), whereas under other GCMs a decrease is projected. BTG for maize is projected to increase under all climate change scenarios by up to 70%. This increase is always lower under dynamic CO_2 conditions due to the CO_2-induced lower irrigation requirements (data not shown). The regional patterns of changes in BTG from maize are shown exemplarily for HadCM3 in Appendix ‘‘2.6.4 Changes in the ratio between blue water consumption and green water consumption (BTG) for maize (HadCM3, SRES A2 emissions scenario)”.

Note that it is crucial to consider the present distribution of temperate cereals and maize when interpreting their global average response to climate change, as that response is the net outcome of climatic changes and impacts within these heterogeneous regions.

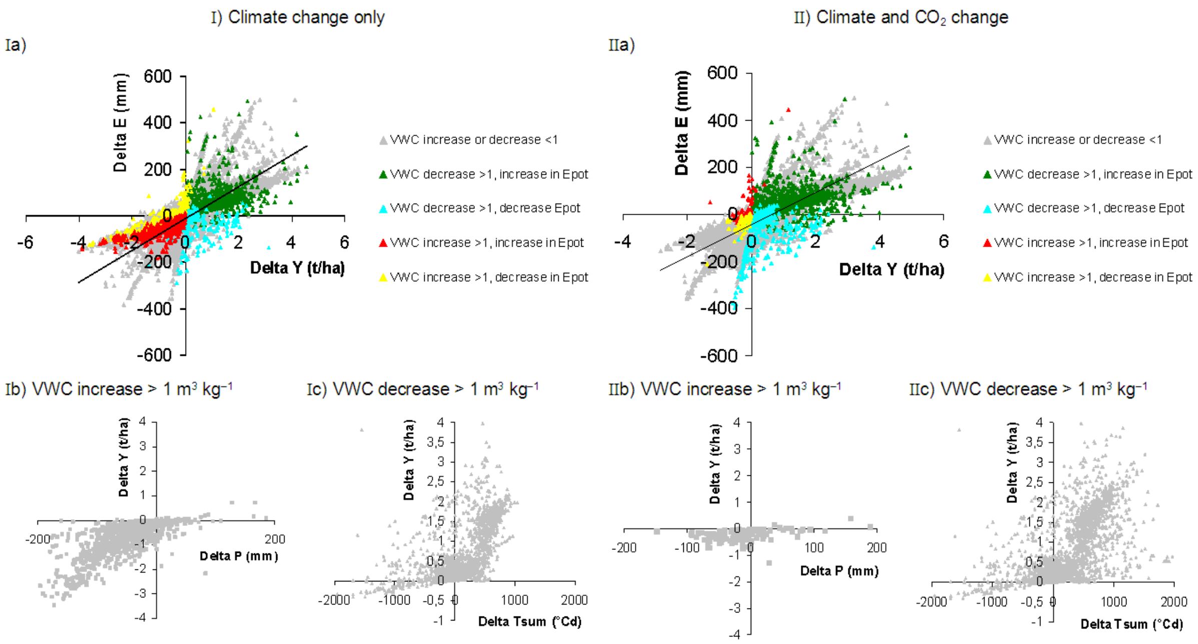


Figure 2.6: Simulated changes in yields (Y), evapotranspiration (E), Precipitation (P), temperature (Tsum) for rainfed maize, presented as differences between the 2041–2070 and 1971–2000 periods, under HadCM3 (I. with constant, II. with dynamic CO_2). Negative (positive) values on the axes represent a decrease (increase). Changes in VWC are in m^3 kg^{-1}. E_{pot}, E, P and Tsum are accumulated over the growing period.

2.4 Discussion

This study is the first to present the spatial distribution of VWC for rainfed and irrigated temperate cereals and maize, globally and at high spatial resolution, for present time and under future projections of climate and CO_2 change. The results demonstrate that climate and CO_2 change will produce a complex spatial pattern of change in VWC, resulting from (partially contrasting) changes in yields and evapotranspiration, and also varying among crop types.

Although a comparison of our results with earlier studies demonstrates a generally good agreement as for the broad patterns, there are marked differences in individual cases, which may be explained by the different estimation methods: while we have employed a process-based model at grid cell level, Hoekstra and Chapagain (2007a) computed their values at national level based on CROPWAT, an FAO model that uses crop coefficients to compute E and that does not consider crop water limitation even in rainfed regions. For example, Hoekstra and Chapagain (2007a) found higher VWC values of temperate cereals in Russia than we did, probably because they used country average climate data which can lead to biased estimations especially in large countries, and because they may have exaggerated values of E due to the omission of water limitations.

It has to be noted that a comparison between modelled and measured data for individual sites (Fig. 2.4a and b) is difficult, since the observations may not be representative for each region due to more intensive management practices of agricultural stations (e.g. mulching, irrigation water management, etc.; see details in Zwart and Bastiaanssen, 2004, and the references therein). Other reasons for the differences could be the possibly incorrect identification of the corresponding grid cells due to missing geographic coordinates in the paper of Zwart and Bastiaanssen (2004), and the fact that we used estimated artificial daily weather data derived from monthly means rather than local meteorological observations. Furthermore, we may regionally overestimate E due to the model assumption that irrigation requirements could always be met, which is an optimistic assumption for the present and especially for the future, since non-renewable water sources (e.g. fossil groundwater resources) are likely to diminish in some regions (Bates et al., 2008). At the same time, our results for irrigated areas can be improved if we assume a higher management intensity (higher LAI_{max}) for irrigated areas (data not shown)—in this case, the CWP values shown in Fig. 2.4a and b would somewhat increase and thus come closer to the measurements.

All in all, models differ in their estimates of VWC for individual crops in specific regions and even globally, and they do not always agree whether the VWC of a crop is higher or lower under irrigated conditions than under rainfed conditions. As analysed by Siebert and Döll (2010), such discrepancies are attributable to a diversity of factors, including different parameterisations of individual processes (e.g. cropping periods, potential evapotranspiration) and different study periods used for comparisons (see ‘‘Differences between irrigated and rainfed conditions, and between CFTs” and ‘‘Comparison with earlier estimates”).

A further source of differences in VWC between studies is the land-use information upon which they are based, and the treatment of inter- and intraannual land-use dynamics. The present study is based on gridded input data (instead of e.g. national data) from a new land-use dataset with up-to-date information about the distribution of rainfed and irrigated crops (Portmann et al., 2010, see Appendix ‘‘2.6.1 Implementation and description of the new land-use dataset”), while earlier studies relied on other, less detailed land-use datasets. Also, in contrast to our study, most other studies did not consider dynamic changes in seasonal phenology and in the length of growing periods. For example, Liu (2009) and Liu et al. (2007) used a crop model with fixed sowing dates (thus not able to simulate shifts in growing periods in response to climate change) and no distinction of irrigated and rainfed crops within a grid cell (i.e. if there is irrigation equipment, all crops in that grid cell were assumed to be irrigated). Further differences in VWC among studies stem from differences in the climate data used and from differences in the definition of VWC and CWP, respectively. For instance, the plant biomass may be expressed as the above-ground biomass (and as dry or fresh matter) or the grain biomass; and the water consumption may include E or only E_T.

Given the dearth of observational data, it cannot be stated with certainty which model approaches are better suited for assessing VWC. However, we believe that the process-based, dynamic and coupled simulation of plant growth, evapotranspiration fluxes, sowing and harvesting dates by the model used here (LPJmL) allows for a more realistic computation of yields, water consumption, and VWC than models in which these processes do neither interact nor respond dynamically to climatic and other environmental changes. As suggested also by Hoff et al. (2010) and other studies (e.g. Siebert and Döll, 2010) in this special issue, the non-trivial discrepancies among different model approaches and between models and measurements require a concerted model intercomparison with standardised input data and a common simulation protocol in order to better understand the drivers and spatio-temporal patterns of VWC.

While we provide an analysis of processes controlling VWC at global and also at regional scale (Fig. 2.6), more detailed analysis of the dynamic interactions of the many processes involved, including their seasonal dynamics, will have to be provided in future studies for individual regions. Further studies will also have to address future changes in VWC under the full range of climate scenarios (while we have focused on only three climate projections under a particular emission scenario here) and also under land-use change scenarios. And finally, while we have accounted for only two crop types here, the present and potential future patterns of VWC of other crops will have to be addressed in forthcoming studies.

A shortcoming of the present LPJmL version is that natural and artificial nutrient availability are represented in combination (and together with other management factors) by the parameter LAI_{max}. Natural or anthropogenic (erosion, degradation, low fertiliser application) nutrient deficiency could limit the realisation of the CO_2 effect, which is why the present results under this effect have to be interpreted as an optimistic estimation. Actually, however, the magnitude of the CO_2 effect falls within the range of observations for crops (see also Rost et al., 2009; Hickler et al., 2008). Note that observational evidence does not convincingly preclude the possibility that the here projected, rather strong effects of increasing CO_2 can be achieved. The different response of both crop types to the CO_2 effect was simulated as expected (stronger response of C3). However, there is still no clear picture of the diverging responses of C3 and C4 plants, especially when comparing enclosure and FACE experiments (Ainsworth et al., 2008).

A further issue is the neglect of potential future changes in management practices that will certainly affect the VWC of crops. While present management is roughly captured via the calibration procedure in this study, upcoming studies may consider the effects of different management options (e.g. those already implemented by Rost et al., 2009) upon yields, water fluxes and, thus, VWC.

2.5 Conclusions

This study is, to our knowledge, the first to present worldwide changes in the virtual water content of crops in response to potential future changes in climate and atmospheric CO_2 concentration. Despite some model-inherent uncertainties, some general conclusions can be drawn.

(1) There is a high potential for improvements in crop water productivity in tropical and subtropical regions, especially in Africa and Southeast Asia, as these regions present the highest VWC at present (compare Fig. 2.2).

(2) High water stress contributes worldwide to high VWC values; additionally, short growing periods in subtropical and temperate regions as well as long growing periods in tropical regions seem to also be connected to high VWC.

(3) Analogous to the marked regional differences under present climatic and management conditions, future patterns of VWC will evolve in a highly dynamic and non-linear way. This response will depend on the detailed regional pattern of climate change, the degree to which CO_2 fertilisation effects can be realised in the field, and the dynamics of underlying processes such as yield levels, water stress, temperature change and lengths of growing periods. Altogether this study shows the potential risk for some regions of becoming less water efficient under climate change and the importance of assuring the positive effects of CO_2 fertilisation by means of adaptation measures such as optimal nutrient management.

(4) Since precipitation is projected to decline in many subtropical regions not only in the scenarios considered here but also in most other climate scenarios (Bates et al., 2008), there is a high risk that VWC will increase in these and other regions (see Fig. 2.6).

(5) As the regional differences in VWC are an important (though not the exclusive) foundation of virtual water trade, the projected changes in VWC may have major consequences for international trade relations. For example, countries that are not food self-sufficient due to water limitations already today (e.g. the Middle East and North African region) will become even more dependent of this trade in the future, while countries that are main exporters of agricultural commodities today may loose part of their capacities (e.g. the US, see Fig. 2.5a and Appendix ‘‘2.6.3 Virtual water content of maize for other GCMs, with constant CO_2”).

Thus—in addition to the dual pressure of regional declines in freshwater supply and increasing demand for food—the potentially adverse future changes in VWC found here pose a challenge to current water management efforts, assumptions about the stationarity of water resources and productivities and established trade relations.

2.6 Appendix

2.6.1 Implementation and description of the new land-use dataset

LPJmL requires as an input the annual fractional coverage per grid cell of each CFT, separately for irrigated and rainfed areas. For this study, we implemented a newly developed dataset that for the first time consistently combines irrigated and rainfed areas within a grid cell (Portmann et al., 2008, 2010) and that contains an updated version (Monfreda et al., 2008; Ramankutty et al., 2008) of the crop distribution databases used in earlier LPJmL studies (e.g., Bondeau et al., 2007; Rost et al., 2008).

Fig. 2.A shows schematically the compilation procedure for the new land-use dataset. The data from Portmann et al. (2010) include maximal monthly harvested areas in a 0.5° resolution, we assumed for each pixel and CFT the month with the highest harvested area to be representative for the annual harvested area. In a first step, we combined the total fractional coverage of a grid cell with cropland and pasture (Ramankutty et al., 2008) and the fractional distribution of each of the irrigated and rainfed crop types (Portmann et al., 2010), which both represent the situation around the year 2000. While the original pasture fractions from Ramankutty et al. (2008) were

taken without modifications, we made sure that the sum of fractions of the individual CFTs in a cell (from Portmann et al., 2010) did not exceed the total agricultural area in a cell from Ramankutty et al. (2008), which could occur e.g. if there is multi-cropping (more than one crop cycle within a year in the same grid cell). We achieved this by proportionally reducing the fractions of each CFT to fit the total cropland fraction. If, in turn, regions classified as cropland by Ramankutty et al. (2008) are not considered by Portmann et al. (2010), we added these additional fractions to our model's ''rainfed others'' CFT category.

In a second step, the thus created land-use dataset for around the year 2000 was extrapolated backward to the year 1700—following the relative changes (aggregated from 5' to 30' resolution) given by the HYDE 3 dataset of the decadal cropland and pasture extent (Klein Goldewijk and van Drecht, 2006)—which is required for a correct model spin-up (see ''2.2.2 Model setup and simulations''). Analogous to an earlier interpolation procedure (Bondeau et al., 2007), we assumed that a CFT's relative fraction of the dynamic total cropland area within a grid cell was constant over time. For the period 2001–2005 (not covered by HYDE), the CFT fractions were assumed to follow the trends over the period 1990–2000.

Since the HYDE data do not provide information about the historical extent of irrigated areas, we assumed a global irrigated area in 1700 of 3 Mha (Stefan Siebert, personal communication). To estimate the temporal evolution of this area, we calculated the global trend from Hoekstra's (1998) decadal data for 1900–1990 and used this trend for the periods 1700–1899 and 1991-2005 as well. Subsequently, the historical irrigated area in each grid cell was calculated as follows:

$$\mathrm{pirr}_{yk} = \frac{\mathrm{pirr}_{00k}}{\mathrm{Girr}_{00}} * \mathrm{Girr}_{y} \qquad \text{(A1)}$$

where pirr_{yk} is the irrigated area in cell k and year y; pirr_{00k} is the irrigated area in cell k in 2000 and Girr_{00} the global irrigated area in 2000 (both from Portmann et al., 2010), and Girr_{y} is the global irrigated area in year y (estimated as described above). When proportionally changing the irrigated and rainfed CFT fractions of 2000 to fit the historical cropland fractions, priority was given to the irrigated fraction as calculated by equation A1. For this, the fractions computed in this step were adapted to simultaneously fit the calculated irrigated cell area and the historical cropland area.

2.6.2 Agricultural management intensity

LPJmL requires as an input the country- and CFT-specific parameter LAI_{max}, representing the agricultural management intensity. This parameter was calculated as explained in ''2.2.3 Calculation of crop yields'' and can be depicted from Fig. 2.B for temperate cereals (a) and maize (b). It appears that developed countries have mainly high LAI_{max} values, fast developing countries have middle LAI_{max} values and developing countries low LAI_{max} values. In countries where a difference in management between the two crops is well known (e.g. in the US and in Argentina), these discrepancies are also reflected by different LAI_{max} values.

To validate at least qualitatively the LAI_{max} parameterisation, we compared the values with FertiStat (2009) values to explore the relation between agricultural management intensity and industrial fertiliser application (N, K_2O, P_2O_5). The comparison (data not shown) revealed the expected general positive relationship between fertiliser application (especially nitrogen) and higher LAI_{max}, though there were numerous exceptions. This is not surprising due to the fact that industrial fertiliser application is only a subgroup of the applied fertilizer (manure application is very important in some countries) and only a very small part of management, which includes also e.g. mechanisation, weed and pest control, use of genetic modified varieties.

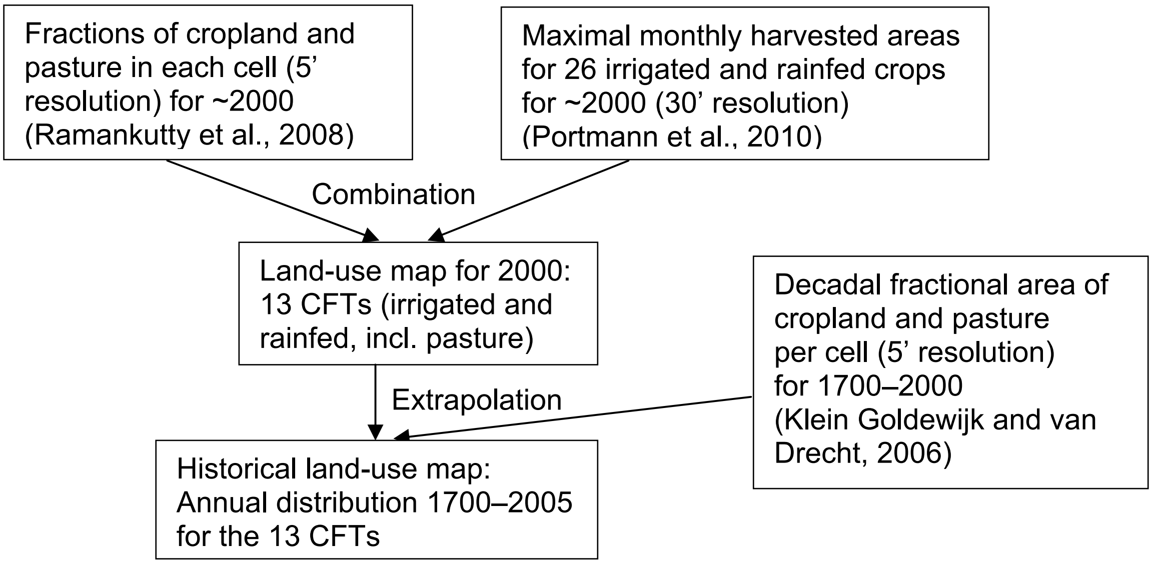


Figure 2.A: Compilation procedure of the land-use dataset for LPJmL.

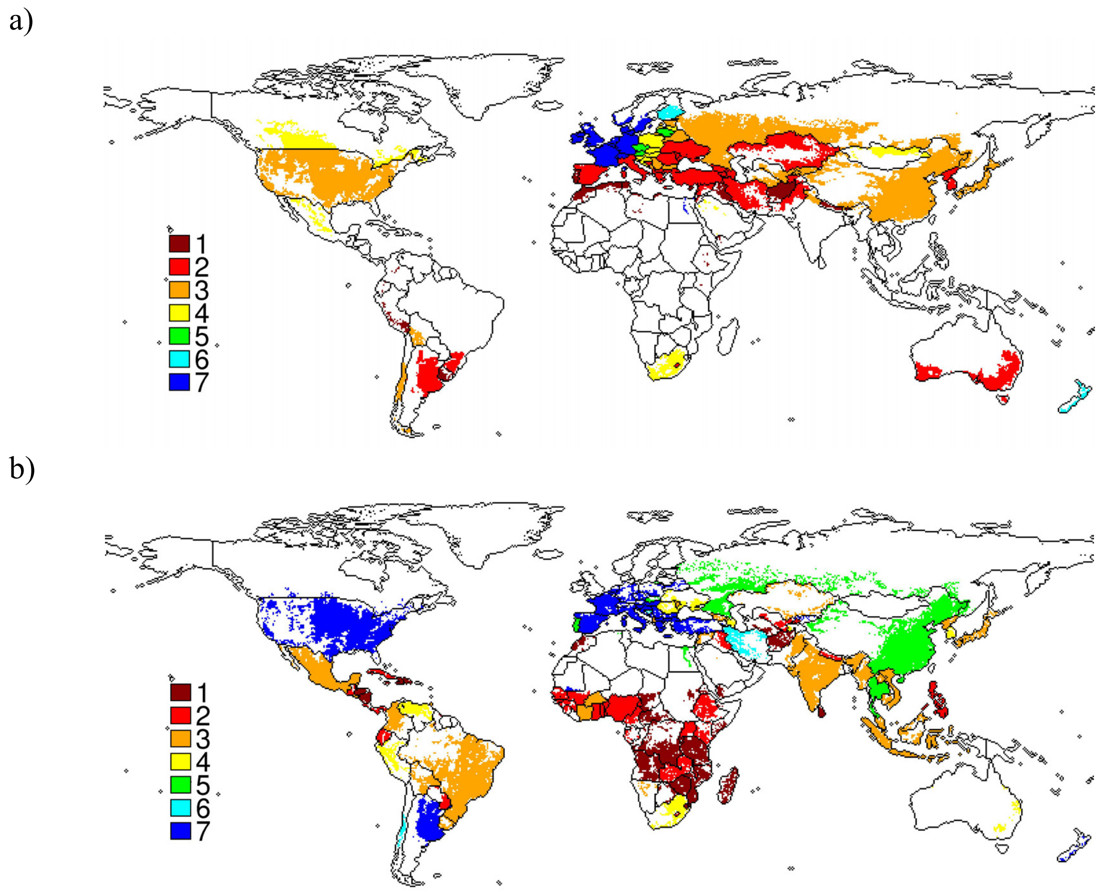
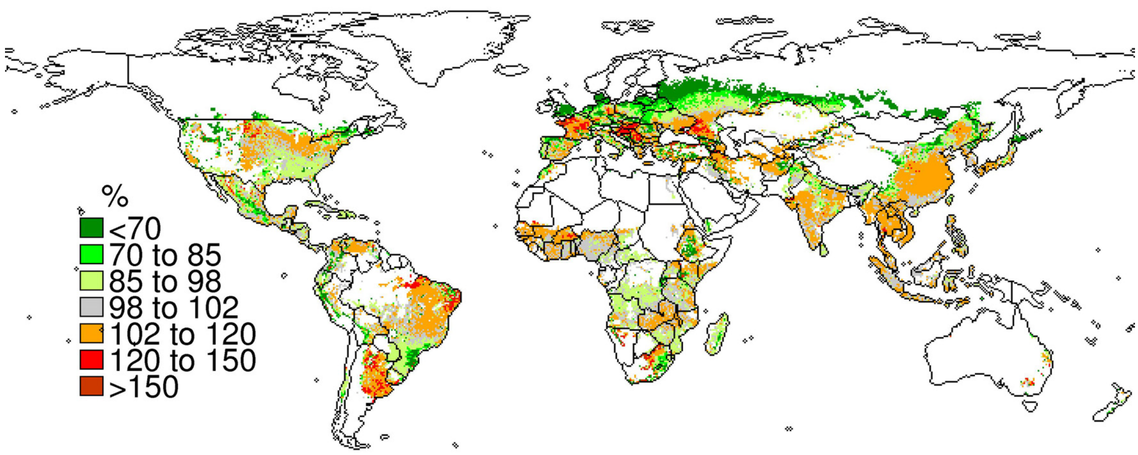


Figure 2.B: Maps of agricultural management intensity (LAI_{max}) for temperate cereals (a.) and maize (b.). Only grid cells with a mean harvested area >0 in the period 1999–2003 are coloured. High (low) LAI_{max} values represent high (low) agricultural management intensity.

2.6.3 Virtual water content of maize for other GCMs, with constant CO_2

Fig. 2.C shows the percent changes in VWC of maize from 1971–2000 to 2041–2070 under the ECHAM5 (a) and CCSM3 (b) climate models (SRES A2 emissions scenario), under conditions of climate change only. See main text for analysis of differences.

a)



b)

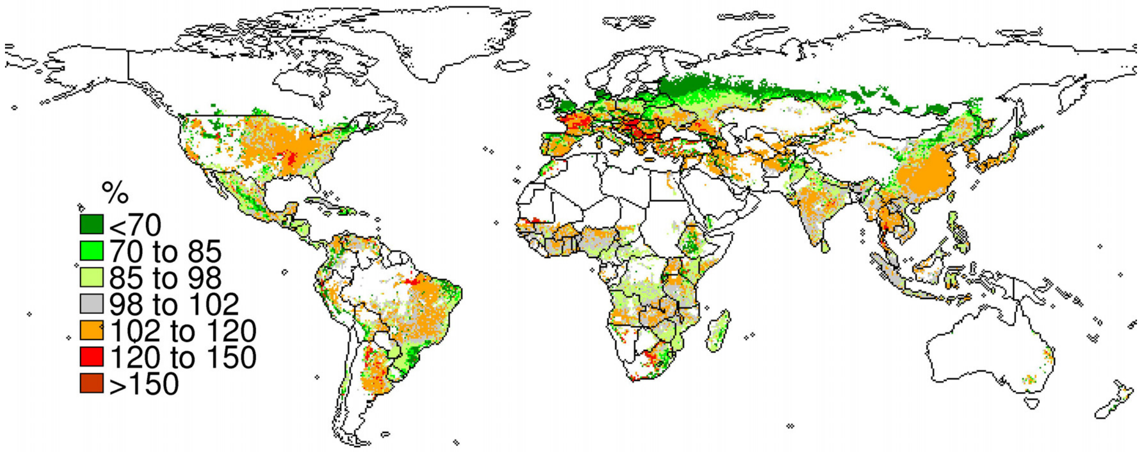


Figure 2.C: Percent changes in VWC of maize (irrigated and rainfed combined; $m^3\ kg^{-1}$) from 1971–2000 to 2041–2070 under the ECHAM5 (a.) and CCSM3 (b.) climate models (SRES A2 emissions scenario), under conditions of climate change only. Values <100% (>100%) represent a decrease (increase) in VWC.

2.6.4 Changes in the ratio between blue water consumption and green water consumption (BTG) for maize (HadCM3, SRES A2 emissions scenario)

Fig. 2.D suggests that BTG increases around the world, mainly due to precipitation decrease in combination with higher temperatures. There are some exceptions in the Near East and China. Three quarters of these exceptions are caused by a more faster maturing of the crop (shorter growing periods) due to higher temperatures (Near East) and higher precipitation during the growing period (China). This reduces the total water consumption and the irrigation water requirements. It has to be noted that the

Near East has already at present much higher BTG than the rest of the world. This is also the reason for the relative low percentage changes of BTG in this region. In China, however, relative low changes in BTG, in combination with low current BTG values, result in high percentage changes.

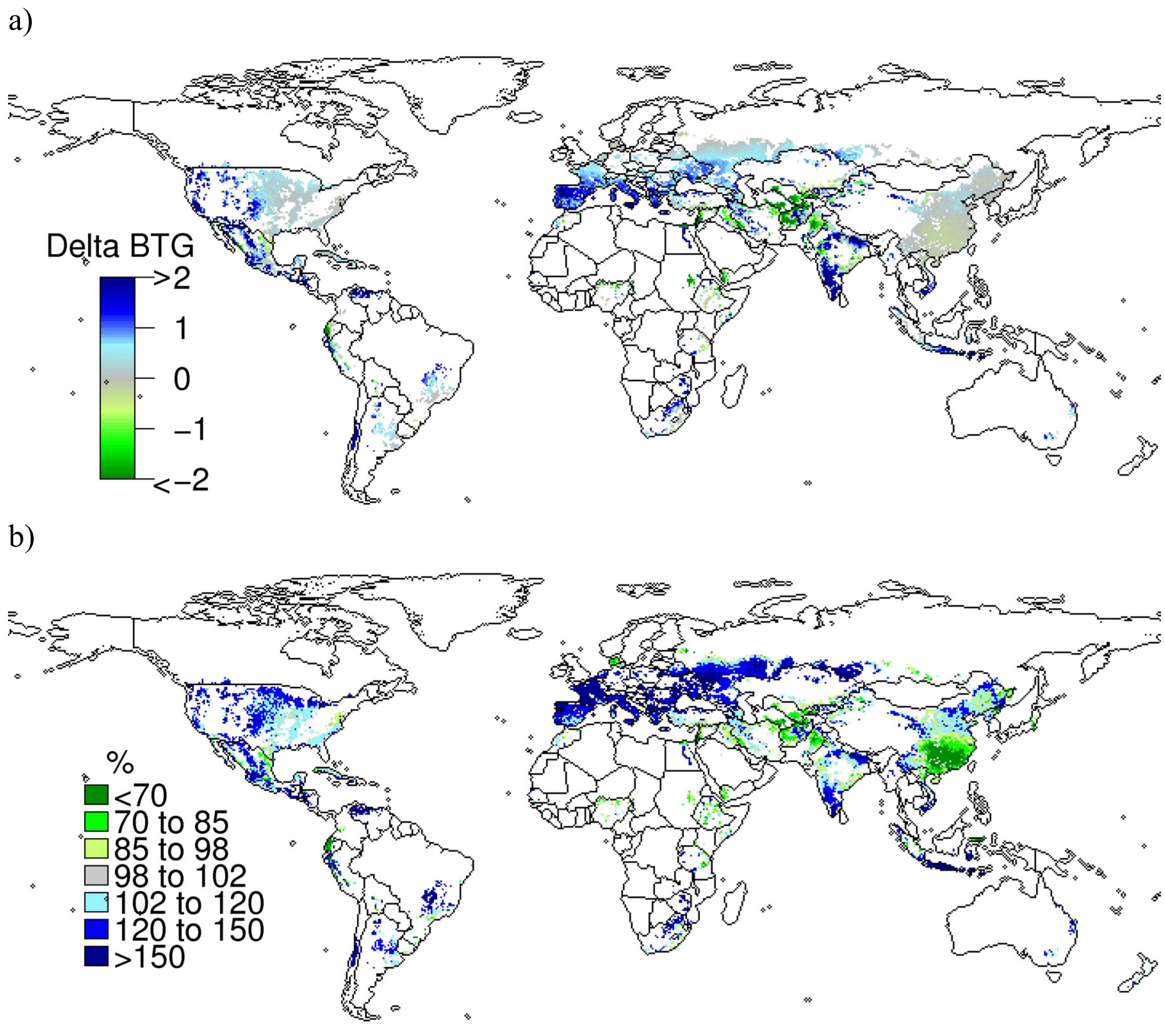


Figure 2.D: Absolute (a.) and relative (b.) changes in BTG of irrigated maize from 1971–2000 to 2041–2070 for the HadCM3 climate scenario (SRES A2 emissions scenario) under climate-change-only conditions.

Acknowledgements

This study was funded by the German Ministry for Education and Research (BMBF), the German Research Foundation (DFG), the European Communities (WATCH Integrated Project, 036946), and the GTZ. We thank Holger Hoff, Louise Karlberg, Hermann Lotze-Campen, Wolfgang Lucht, Ursula Heyder and Sibyll Schaphoff for valuable discussions, comments, and technical support.

We also thank the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model for the provision of the climate projections. We gratefully acknowledge Petra Döll, Felix Portmann and Stefan Siebert for providing the MIRCA2000 land-use dataset, and two anonymous reviewers for constructive comments.

Chapter 3

Climate change impacts on agricultural yields[2]

Christoph Müller, Alberte Bondeau, Alexander Popp, Katharina Waha and Marianela Fader

Abstract

Since yield changes in the future may influence the capacity of humanity to produce the food needed and could have very positive or negative consequences for the food security and economy of many countries, we assessed the impacts of future climate change for crop yields. We calculated percent changes in agricultural productivity with the model LPJmL between two 10-year periods: 1996-2005 and 2046-2055 with 3 different emission scenarios (SRES A1b, A2, B1) and 5 different general circulation models: CCSM3, ECHAM5, ECHO-G, GFDL and HadCM3. We estimated the CO_2 fertilization effects by first accounting for full effect according to the prescribed SRES atmospheric CO_2 concentrations, and second, keeping atmospheric CO_2 concentrations constant at 370 ppm after 2000. Population growth projections from the corresponding SRES scenarios were taken to assess the impact of changes in crop yields and in population size on food self-sufficiency.
At global scale, the CO_2 fertilization effect determines the sign of yield changes. If CO_2 fertilization is fully accounted for, crop yields rise globally by 8-22% in 2050 relative to 2000, while yields decrease globally between 0-13%, if CO_2 fertilization is not taken into account.
At national and sub-national scale, however, differences in climate projections often have larger influence on changes in crop yields than the CO_2 fertilization effect. Increasing crop yields may be expected in regions currently constrained by too low temperatures as in the northern high latitudes and in mountainous regions. Here, all 30 model runs uniformly indicate increases in crop yields by 2050. On the contrary, there is hardly any location where all model runs uniformly indicate decreases in crop yields. If all effects of CO_2 fertilization

[2] Part of this chapter was published as Müller, C., Bondeau, A., Popp, A., Waha, K., Fader. M. (2010): Climate change impacts on agricultural yields. Background note to the World Development Report 2010. http://siteresources.worldbank.org/INTWDR2010/Resources/5287678-1255547194560/WDR2010_BG_Note_Mueller.pdf. However, some contents of this background note are not included in this chapter. And some numbers were updated in this chapter and thus differ from the ones in the published note.

are excluded, many regions and especially tropical croplands are uniformly projected in all 15 climate scenarios to experience decreases. It has to be noted that long term positive effects of CO_2 fertilization are subject to scientific debate, not only in the realization of the effects for yields, but also concerning the quality of agricultural products and the susceptibility to insect pests, when they are grown under increased CO_2.

In 7 out of 10 world regions, the mean impact indicates rising crop yields in 2046-2055 compared to 1996-2005. Population growth outweighs however the effect: even the most optimistic scenarios with increasing crop yields on current cropland cannot mitigate the significant decrease in food self-sufficiency in 6 out of 10 regions. Improved management and technological change, as well as an expansion of agricultural land may thus be inevitable to meet future food demand.

3.1 Introduction

Crop yields are not only an indication of how efficient the agricultural sector uses the productive land resource, but also, in combination with climatic conditions and management intensities, an indicator of the potential for increasing agricultural production. Since future population change and changes in lifestyle are very likely to demand increases in agricultural production, looking at the future development of yields is essential in order to realize these increases, mitigate negative effects and successfully adapt to adverse trends.

Future development of crop yields are subject to several uncertainties: (a) changes in climate (Solomon et al., 2007), (b) changes in atmospheric CO_2 concentrations and the subsequent impact on crop water productivity and CO_2 fertilization (Long et al., 2006; Tubiello et al., 2007), (c) changes in management/breeding, (d) changes in cropping area and (e) changes in socioeconomic aspects, like prices, access to market, subsidies, etc. Here, we account for the first two drivers only: climate change and CO_2 fertilization by employing different scenarios.

Many other efforts have been made in this direction, especially at regional scale. The Intergovernmental Panel on Climate Change resumes in chapter 5 of the 4th Assessment Report the impacts for the agricultural sector as generally negative for low and mid-latitudes and positive for high latitudes, especially if warming stays bellow 2-3°C. Higher warming could nevertheless expand negative impacts to many more regions (Easterling et al., 2007). However, there are few studies accounting comprehensively for changes in yields of the major crops worldwide considering different emission scenarios, different climate projections and assessing separately the whole range of CO_2 fertilization. For example Tan and Shibasaki (2003) looked globally at the effects of climate change on crop yields with the EPIC model and came to the conclusion that global warming would be harmful for most of the countries. However, they did not take into account the CO_2 fertilization effect. Rosenzweig and Parry (1994) integrated many regional studies about the consequences of a doubling of CO_2 concentrations on crop yields, using three different GCMs and came to the conclusion that the decrease in crop production would be small but developing countries would be most affected. However, they had very few model sites in Africa. Parry et al. (2005) assesses the implications of climate change for food production and risk of hunger using the model IBSNAT. They stated that Africa is the region with the greatest risk, that CO_2 stabilization should be rather in the 550ppm than in the 750ppm level to avoid most of the risk and that development pathways have much influence in the impacts on risk of hunger, being the yield reduction in globalized scenarios greater than in regionalized scenarios. They, however, accounted only for rice, maize, wheat and soybeans, had only 112 model sites in 18 countries and used only in some parts of this work different GCMs, actually most of the conclusions were based on HadCM3 only.

This short review highlights the need of a study accounting globally for the effects of climate and CO_2 change on crop yields of the most important commodities, considering a wide range of GCMs and development scenarios. And these are at the same time the aims of this work.

3.2 Methods

We employed the LPJmL model (Bondeau et al., 2007) to compute the effects of climate change and CO_2 fertilization on yields of major crops globally at a spatial resolution of 0.5°x0.5°. Yield simulations are based on process-based implementations of gross primary production, growth- and maintenance respiration, water-stress, and biomass allocation, dynamically computing the most suitable crop variety and growing period in each grid cell as described in more detail by Bondeau et al. (2007) and Fader et al. (2010).

We present percent changes in agricultural productivity between two 10-year periods: 1996-2005 and 2046-2055, representing the average productivity of the years 2000 and 2050. Management intensity has been calibrated to match national yield levels as reported by FAOSTAT for the 1990s (Fader et al., 2010). National and regional agricultural productivities are based on calorie- and area-weighted mean crop productivity of wheat, rice, maize, millet, field pea, sugar beet, sweet potato, soybean, groundnut, sunflower, and rapeseed. The spatial pattern of growing areas and the crop-specific share of irrigated area are based on Portmann et al. (2008, 2010), Ramankutty et al. (2008) for the year 2000, see Fader et al. (2010).

We computed 30 different scenarios from 1950 to 2055 for 3 different emission scenarios (SRES A1b, A2, B1) (Nakicenovic and Swart, 2000), each implemented by 5 different general circulation models (GCM): CCSM3 (Collins et al., 2006), ECHAM5 (Jungclaus et al., 2006), ECHO-G (Min et al., 2005), GFDL (Delworth et al., 2006), and HadCM3 (Cox et al., 1999). Climate data for these GCM-projections were generated by downscaling the change rates of monthly mean temperatures and monthly precipitation to 0.5° resolution by bi-linear interpolation and superimposing these monthly climate anomalies (absolute for temperature, relative for precipitation and cloudiness) on the 1961–1990 average of the observed climate (New et al., 2000; Österle et al., 2003). Since there was no information about the number of wet days in the future, these were kept constant after 2003 at the 30-year average of 1971–2000.

To assess the range of CO_2 fertilization uncertainty (e.g. Long et al., 2006; Tubiello et al., 2007), we computed each of the 15 scenarios twice: first, taking into account full CO_2 fertilization effects according to the prescribed SRES atmospheric CO_2 concentrations, and second, keeping atmospheric CO_2 concentrations constant at 370 ppm after 2000. Production area was static at the prescribed year-2000 pattern. Relative management levels were calibrated to match observed current production levels as described by Fader et al. (2010) but sowing dates were assumed to be adapted to climate change as described by Bondeau et al. (2007) and for wheat, maize, sunflower, and rapeseed we assume also adaption in selecting suitable varieties. Modelling constraints do not allow for adapting varieties for all other crops here. However, we do not account for the uncertainty in management changes as we here consider one setting only.

Population growth projections were taken from Nakicenovic and Swart (2000) to assess the impact of changes in crop yields and in population size on food self-sufficiency.

3.3 Results

Data on changes in crop yields are presented as country- and region-specific percent change rates. The overall changes in crop yields on current cropland (in percent relative to 1996-2005) are shown in Figure 3.1. Impacts on yields are shown in relation to projected changes in population (Nakicenovic and Swart, 2000) and the resulting impact on regional self-sufficiency rates. In 7 out of 10 world regions, the mean impact indicates rising crop yields in 2046-2055 compared to 1996-2005.

However, depending on climate scenario and the assumptions on effectiveness of CO_2 fertilization, all regions may experience significant decreases in crop yields as well as significant increases. The most important factor is the uncertainty in CO_2 fertilization, which outweighs the differences in climate scenarios. Figure 3.2 depicts the difference between changes in crop yields with (left hand panel) and without (right hand panel) CO_2 fertilization effects, aggregated at national level and sub-national level for larger countries (Australia, Brazil, Canada, China, India, Russia, USA). Whether or not farmers will be able to attain increased crop yields under elevated atmospheric CO_2 concentrations will much depend on the availability of additional inputs, especially nitrogen (Tubiello and Ewert, 2002). In regions where current inputs are already constraining crop yields considerably (Neumann et al., 2010), major improvements are required to provide additional nitrogen inputs. Self-sufficiency in food production is likely to decrease in most regions as in many cases population growth outweighs even increasing crop yields. As a consequence, even the most optimistic scenarios with increasing crop yields on current crop land cannot mitigate the significant decrease in food self-sufficiency in 6 out of 10 regions (Figure 3.1).

Increasing crop yields may be expected in regions currently constrained by too low temperatures as in the northern high latitudes and in mountainous regions (Figure 3.3, green areas in panel b). Here, all 30 model runs uniformly indicate increases in crop yields by 2050. On the contrary, there is hardly any location where all model runs uniformly indicate decreases in crop yields (Figure 3.3, red areas in panel a). If all effects of CO_2 fertilization are excluded, many regions and especially tropical croplands are uniformly projected in all 15 climate scenarios to experience decreases in crop yields (Figure 3.3, panel b).

Table 3.1 provides an overview of the regional climate change and CO_2 fertilization impacts on crop yields. It has to be noted that the beneficial effects of CO_2 fertilization are subject to heavy debate (Long et al., 2006; Tubiello et al., 2007) and that current management constraints cast considerable doubt on obtaining full CO_2 fertilization benefits in many regions.

Differences in projected crop yields vary strongly between GCM climate projections, ranging between 1.9% in PAS and 46.3% in PAO (data not shown). The largest range between different GCM projections is computed for the region of PAO, where crop yields are projected to increase by 34.7% (CCSM) or decrease by 11.6% (HADCM) under the A1b scenario with CO_2 fertilization effects (data not shown).

3.4 Discussion

There is considerable uncertainty in the future development of crop yields on current cropland, ranging from a general decrease by 14% to a general increase by 22% in 2050 relative to 2000 (data not shown). The largest uncertainty is the effect of CO_2 fertilization, which principally can increase crop yields considerably due to enhanced carbon assimilation rates as well as improved water productivity (Tubiello et al., 2007). However, to which extent this yield increase will be obtained by farmers is highly uncertain: First of all, increased carbon assimilation rates can only be converted into productive plant tissue or the only economically relevant part, the harvested storage organs, if sufficient nutrients are available to sustain the additional growth. Wherever growth is already constrained by nutrient limitations, additional growth will

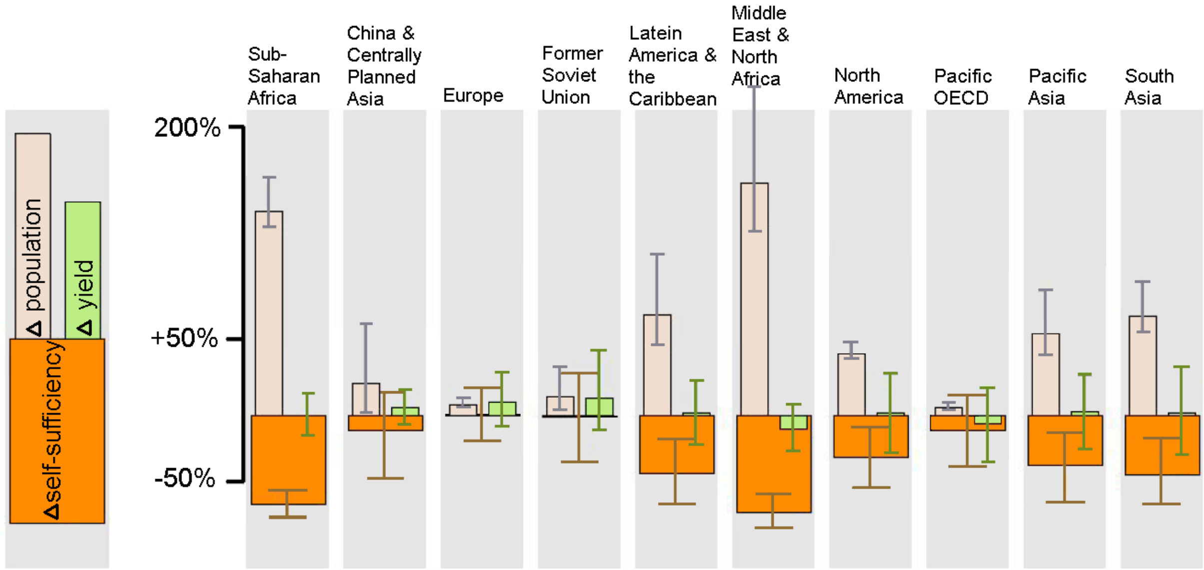


Figure 3.1: Mean change in crop yields (green bars) from 1996-2005 to 2046-2055 in all 30 scenarios considered here. Whiskers indicate the range of impacts, which is mainly determined by the effectiveness of CO_2 fertilization. Tan-coloured bars indicated projected changes in population (Nakicenovic and Swart, 2000). Most regions are likely to experience significant decreases in self-sufficiency, because population growth often offsets even increasing crop yields.

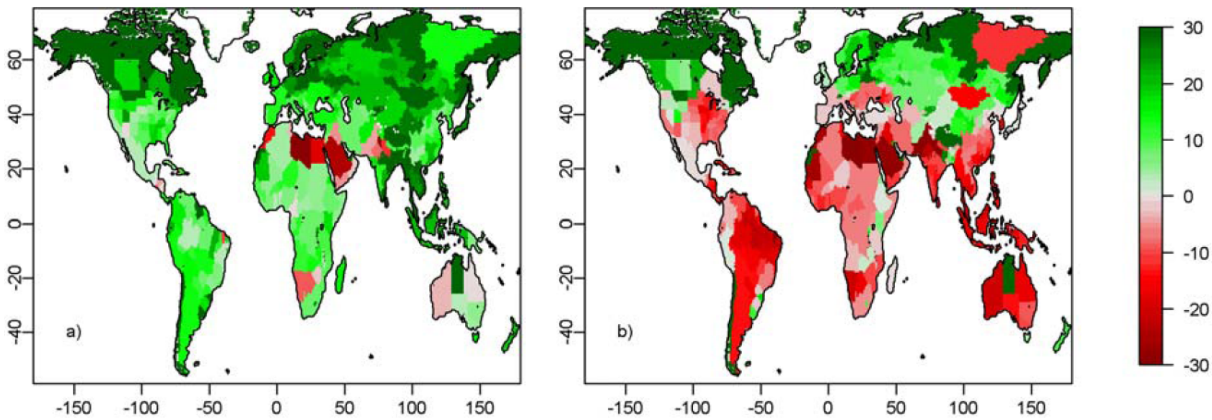
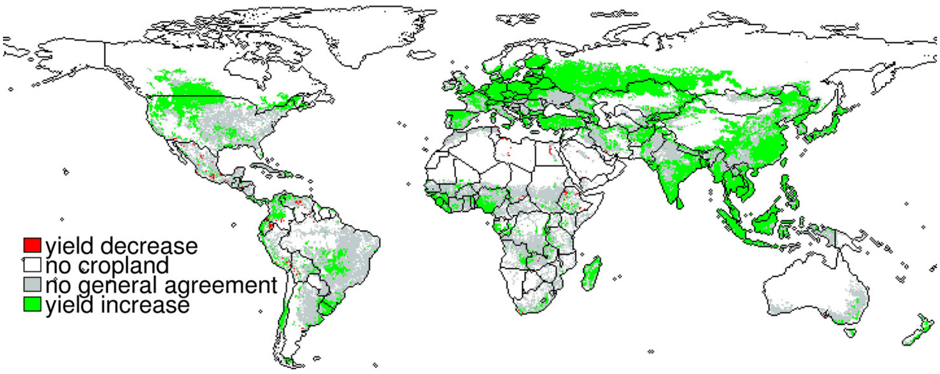


Figure 3.2: All climate scenario mean (3 emission scenarios in 5 GCMs) impact on (sub-) national crop yields in 2050 (2046-2055 average), expressed in percent change relative to 2000 (1996-2005 average). Panel a) with full CO_2 fertilization, panel b) without

be very limited. On top of that, there is some likelihood that the quality of agricultural products decreases under increased CO_2 fertilization, as e.g. the protein content diminishes (e.g. Taub et al., 2008) and that crops grown under elevated CO_2 concentrations are more susceptible to insect pests (e.g. Dermody et al., 2008; Zavala et al., 2008).

At global or regional scale, the CO_2 fertilization effect determines the sign of yield changes. If CO_2 fertilization is fully accounted for, crop yields rise globally by 8-22% in 2050 relative to 2000, while all regions experience a decrease in crop yields (0-14%) (data not shown), if CO_2 fertilization is not taken into account. At national and sub-national scale, however, differences in climate projections often have larger a)



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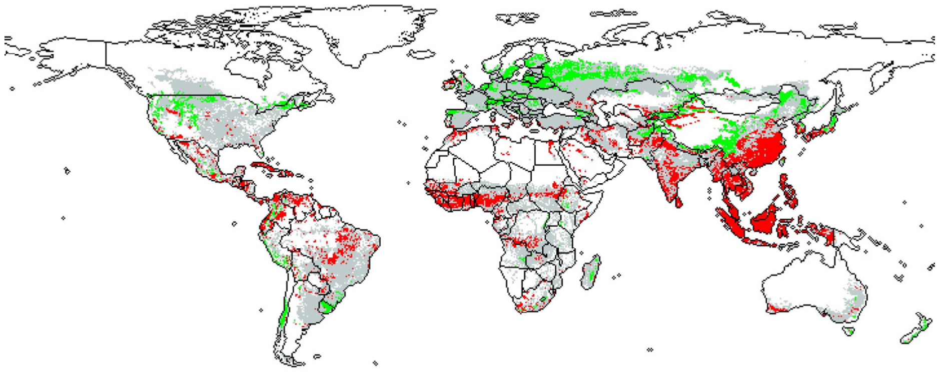

Figure 3.3: Multi-scenario agreement on the direction of changes in yields. Panel a) shows the overall agreement in all scenarios with CO_2 fertilization, while panel b) shows the overall agreement in all scenarios without CO_2 fertilization. The general agreement in all 30 scenarios can be deduced from these to figures: if there is agreement on yield increase without CO_2 fertilization, this is also true with CO_2 fertilization (green areas in panel b) and if there is agreement on yield decreases with CO_2 fertilization, this is also true without CO_2 fertilization (red areas in panel a).

Table 3.1: Regional 5-GCM-mean climate change and CO_2 fertilization impacts on crop yields (percent change in 2046-2055 relative to 1996-2005) on current (2000) crop land.

	full CO_2 fertilization				**no CO_2 fertilization**			
	A1b	**A2**	**B1**	**mean**	**A1b**	**A2**	**B1**	**mean**
AFR	8.4	7.8	6.8	7.5	-8.2	-8.5	-5.9	-7.6
CPA	15.8	15.4	11.8	14.3	-3.6	-3.7	-2.9	-3.4
EUR	17.5	16.7	16.7	16.8	0.8	-0.3	3.7	1.2
FSU	21.4	22.3	21.4	21.4	-0.5	-0.2	4.3	0.9
LAM	9.5	12.2	13.3	11.8	-11.3	-9.4	-3.7	-8.2
MEA	-3.0	-0.7	-2.5	-2.1	-16.6	-14.5	-13.2	-14.8
NAM	10.6	11.6	14.7	12.2	-10.3	-9.3	-1.8	-7.1
PAO	3.3	3.6	4.6	3.5	-15.0	-14.7	-9.8	-13.5
PAS	22.8	23.0	19.9	21.9	-18.5	-18.0	-11.7	-16.0
SAS	21.3	24.6	14.6	19.8	-18.9	-15.3	-14.4	-16.4
World	12.4	13.1	12.5	12.6	-8.2	-7.6	-3.5	-6.5

influence on changes in crop yields than the CO_2 fertilization effect. The selection of climate projections is therefore a major source of uncertainty for the assessment of national and sub-national climate change impacts on crop yields. However, it is not possible to identify a "most likely" climate change pattern. It is possible – to some extent – to identify hot spot regions of climate change impacts on yields, as e.g. in Figure 3.3.

Results presented here only indicate the scope of climate-related impacts on crop yields. Besides uncertainties in future development of drivers (climate change, CO_2 fertilization effect, management, technological change), modeling of crop yields at large scales adds to the overall uncertainty as many processes are necessarily implemented in a simplified manner only. If farmers have access to a broad selection of crop varieties, they are likely to select varieties most suited for the local growing conditions. That means that farmers will adapt to climate change and altered growing periods, if possible (e.g. Reidsma et al., 2009). The model LPJmL considers such adaptation processes in management only to a limited extent. While the sowing date is based on the last 20 years of experience and therefore adapts to changing climate conditions, crop varieties are only adapted for wheat, maize, sunflower, and rapeseed, for which the model internally computes the most suitable variety (Bondeau et al., 2007). For all other crops considered here, this is currently not possible as parameters are lacking.

The selection of different crop varieties yields the potential to greatly affect yields. Our simulations show that winter wheat varieties become suitable in more northern locations as temperatures rise. Winter varieties are typically higher-yielding varieties so that yield levels rise considerably with the switch from summer to winter varieties. This switch can be observed for wheat in north-east Europe, southern Canada, and mountainous regions.

Even the most optimistic scenarios lead to decreasing food self-sufficiency ratios in most regions (Figure 3.1) at current consumption patterns and technology levels. Improved management and technological change, as well as an expansion of agricultural land are thus inevitable to meet future food demand.

3.5 Conclusions

Projections of future crop yields are highly uncertain. At global to regional scale, CO_2 fertilization has the potential to generally increase crop yields on current crop land. However, it is highly unlikely that yield increases due to CO_2 fertilization will be fully achieved in most regions, as long term positive effects are subject to scientific debate and increased yield levels require also adaptations in management (Long et al., 2006; Tubiello and Ewert, 2002; Tubiello et al., 2007). Differences in climate patterns are a major source of uncertainty in local and national yield projections, as especially precipitation patterns differ considerably between GCMs. The range of modeled impacts on yields therefore is only an indication on the locations' susceptibility to climate change and for the necessity of adaptation measures. Future food demand will only be met if improved management and technological change will be able to increase crop yields considerably or if agricultural land is expanded. Even the most optimistic projections on future crop yields lead to decreasing food self-sufficiency ratios in most regions.

3.6 Appendix

Country-to-region mapping for regional aggregation of results.

AFR	CPA	EUR	FSU	LAM
Sub-Saharan Africa	**Centrally-Planned Asia**	**Europe**	**Former Soviet Union**	**Latin America**
Angola	Cambodia	Albania	Azerbaijan, Republic of	Argentina
Benin	China	Austria	Belarus	Belize
Botswana	Laos	Belgium-Luxembourg	Georgia	Bolivia
Burkina Faso	Mongolia	Bosnia and Herzegovina	Kazakhstan	Brazil
Burundi	Viet Nam	Bulgaria	Kyrgyzstan	Chile
Cameroon		Croatia	Moldova, Republic of	Colombia
Central African Republic		Czech Republic	Russian Federation	Costa Rica
Chad		Denmark	Tajikistan	Cuba
Congo, Dem Republic of		Estonia	Turkmenistan	Dominican Republic
Congo, Republic of		Finland	Ukraine	Ecuador
Côte d'Ivoire		France	Uzbekistan	El Salvador
Djibouti		Germany		French Guiana
Equatorial Guinea		Greece		Guatemala
Eritrea		Hungary		Guyana
Ethiopia		Iceland		Haiti
Gabon		Ireland		Honduras
Ghana		Italy		Mexico
Guinea		Latvia		Nicaragua
Guinea-Bissau		Lithuania		Panama
Kenya		Macedonia,The Fmr Yug Rp		Paraguay
Lesotho		Netherlands		Peru
Liberia		Norway		Suriname
Madagascar		Poland		Uruguay
Malawi		Portugal		Venezuela
Mali		Romania		
Mauritania		Slovakia		
Mozambique		Slovenia		
Namibia		Spain		
Niger		Sweden		
Nigeria		Switzerland		
Rwanda		Turkey		
Senegal		United Kingdom		
Sierra Leone		Yugoslavia, Fed Rep of		
Somalia				
South Africa				
Sudan				
Swaziland				
Tanzania, United Rep of				
Togo				
Uganda				
Western Sahara				
Zambia				
Zimbabwe				

MEA	NAM	PAO	PAS	SAS
Middle East/North Africa	**North America**	**Pacific OECD**	**Pacific Asia**	**South Asia**
Algeria	Canada	Australia	Indonesia	Afghanistan
Egypt	United States of America	Japan	Korea, Dem People's Rep	Bangladesh
Iran, Islamic Rep of		New Zealand	Korea, Republic of	Bhutan
Iraq			Malaysia	India
Israel			Papua New Guinea	Myanmar
Jordan			Philippines	Nepal
Kuwait			Solomon Islands	Pakistan
Libyan Arab Jamahiriya			Thailand	Sri Lanka
Morocco				
Oman				
Saudi Arabia				
Syrian Arab Republic				
Tunisia				
United Arab Emirates				
Yemen				

Chapter 4

Internal and external green-blue agricultural water footprints of nations, and related water and land savings through trade[3]

Marianela Fader, Dieter Gerten, Markus Thammer, Jens Heinke, Hermann Lotze-Campen, Wolfgang Lucht, and Wolfgang Cramer

Abstract

The need to increase food production for a growing world population makes an assessment of global agricultural water productivities and virtual water flows important. Using the hydrology and agro-biosphere model LPJmL, we quantify at 0.5° resolution the amount of blue and green water (irrigation and precipitation water) needed to produce one unit of crop yield, for 11 of the world's major crop types. Based on these, we also quantify the agricultural water footprints (WFP) of all countries, for the period 1998–2002, distinguishing internal and external WFP (virtual water imported from other countries) and their blue and green components, respectively. Moreover, we calculate water savings and losses, and for the first time also land savings and losses, through international trade with these products. The consistent separation of blue and green water flows and footprints shows that green water globally dominates both the internal and external WFP (84% of the global WFP and 94% of the external WFP rely on green water). While no country ranks among the top ten with respect to *all* water footprints calculated here, Pakistan and Iran demonstrate high absolute *and* per capita blue WFP, and the US and India demonstrate high absolute green *and* blue WFPs. The external WFPs are relatively small (6% of the total global blue WFP, 16% of the total global green WFP). Nevertheless, current trade of the products considered here saves significant water volumes and land areas (~263 km^3 and ~41 Mha, respectively, equivalent to

[3] Reproduced under the Creative Commons Attribution 3.0 License from Fader, M., Gerten, D., Thammer, M., Heinke, J., Lotze-Campen, H., Lucht, W., and Cramer, W.: Internal and external green-blue agricultural water footprints of nations, and related water and land savings through trade. Hydrol. Earth Syst. Sci. 15, 1641–1660, 2011. http://www.hydrol-earth-syst-sci.net/15/1641/2011/hess-15-1641-2011.pdf

5% of the sowing area of the considered crops and 3.5% of the annual precipitation on this area). Relating the proportions of external to internal blue/green WFP to the per capita WFPs allows recognizing that only a few countries consume more water from abroad than from their own territory and have at the same time above-average WFPs. Thus, countries with high per capita water consumption affect mainly the water availability in their own country. Finally, this study finds that flows/savings of both virtual water and virtual land need to be analysed together, since they are intrinsically related.

4.1 Introduction

About 70% of current water withdrawals are for agricultural production (Molden et al., 2007b), and it is expected that population growth, economic development, urbanization, dietary changes and climate change will further increase water demand for food production in the future (Rosegrant and Sombilla, 1997; Vörösmarty et al., 2000; Steinfeld et al., 2006; Liu and Savenije, 2008; Liu et al., 2008). The global consumption of "blue" water (taken from rivers, reservoirs, lakes and aquifers and used for irrigation) presently amounts to 927–1660 $km^3\ yr^{-1}$ according to recent estimates (Rost et al., 2008; Hoff et al., 2010). However, about 3000 to 6000 $km^3\ yr^{-1}$ of "green" water (precipitation stored in the soil and evapotranspired on cropland) are consumed in addition to sustain rainfed agriculture and parts of irrigated agriculture (Rost et al., 2008; Liu et al., 2009; Hoff et al., 2010). These numbers highlight the outstanding contribution of green water to crop production and, thus, the need to consider this resource in water availability and water scarcity studies (Rockström et al., 2009).

Regional differences in the amount of water needed to produce a unit of crop biomass or yield (i.e. the virtual water content, VWC) can benefit the mitigation of regional water scarcity. Water-scarce countries often import water-intensive agricultural products from water-abundant countries, or from countries where VWC is lower due to more beneficial climate (and management) conditions (e.g. Oki and Kanae, 2004; Hoekstra and Chapagain, 2007b; Yang and Zehnder, 2007). Thus, together with the traded commodities, countries trade the water that was needed for their production (though in virtual form, since it is not physically present in the product). This is called virtual water flow (VWF) or virtual water trade. It is important to differentiate between green and blue virtual water contents and flows in agriculture, because blue water can be redirected more easily to other purposes. This is why blue water has higher opportunity costs (Hoekstra, 2010) and its use has environmental impacts other than green water use (see e.g. Pfister et al., 2009, for consequences of blue water consumption for cotton production).

The water footprint (WFP), developed by Hoekstra and Hung (2002), is a measure of the water intensity and origin of the products consumed by a country, a person or a company, considering both own production (internal WFP, mostly derived for a country) and imports from other countries (external WFP – see Glossary of terms used herein at the end of the text). In the study by Hoekstra and Chapagain (2007b), the global water footprint for a wide range of agricultural, livestock and industrial goods was estimated to be 7450 $km^3\ yr^{-1}$ in absolute terms and 1240 $m^3\ yr^{-1}$ on a per capita basis, however with pronounced differences among countries. For example, North America and Western Europe appear to have much higher per capita WFPs than China and most South African countries. The global external WFP was reported to account for 16% of the total WFP (Hoekstra and Chapagain, 2007b).

Some recent global (modelling) studies explicitly accounted for the contributions of green and blue water to international VWFs and WFPs, though with several shortcomings. For example, the studies by Chapagain et al. (2005), Yang et al. (2006) and Aldaya et al. (2010) were restricted to a narrow selection of commodities or crops, they were not able to account explicitly for the dynamic interactions between soil moisture and plants, and they were based on VWC calculated at country or state level while neglecting country-internal differences. Some of these shortcomings were overcome by the study of Hanasaki et al. (2010) which, however, did not consider the coexistence of different crop types in a grid cell and focused on virtual water exports only. The grid-based study by Mekonnen and Hoekstra (2010a) was restricted to wheat and did not consider plant physiologic water stress under irrigated conditions (i.e. when due to plant hydraulic traits, soil water supply remains below atmospheric demand even if the soil is saturated; Gerten et al. 2004, 2007). A new journal article by Mekonnen and Hoekstra (2010b), which is still under review, quantified WFPs based on grid cell VWCs for a large list of commodities using the same method. Liu et al. (2009) and Liu and Yang (2010) used a crop model with systematic calculations for growing periods (choosing the one with the maximal yield output, which does not reflect the reality everywhere). Furthermore, to our best knowledge, the intimate connection between green water use and land resources was not addressed quantitatively in any WFP study, which would be a step forward in the analysis and quantification of trade-offs for agricultural water use, as pointed out by Yang and Zehnder (2007).

The present global-scale study advances the field by specifically quantifying both the green and the blue internal and external WFPs of countries for a majority of the world's crop types, based on a process-detailed and high-resolution (0.5°) representation of the underlying VWC as computed by the LPJmL dynamic global vegetation and water balance model (Bondeau et al., 2007; Rost et al., 2008). Additionally, this is the first study quantifying virtual land savings associated with virtual land flows.

4.2 General modelling approach and data

4.2.1 General characteristics of the LPJmL model

LPJmL is a process-based, eco-hydrological biosphere and agrosphere model that simulates carbon and water stocks and fluxes in direct coupling with vegetation dynamics. It considers nine plant functional types that represent the variety of woody and herbaceous vegetation types at biome level (Sitch et al., 2003); pasture (managed grassland); and eleven crop functional types (CFTs) that represent a number of the world's major crop types (temperate cereals, maize, rice, tropical cereals, temperate roots, tropical roots, rapeseed, groundnuts, soybeans, pulses, sunflower; for details see Bondeau et al., 2007; Waha et al., 2011).

The CFTs considered in the model version used here cover approximately 53% of the world's cropping area. (Note that the remaining crops are also included, but since they are collectively and preliminarily parameterized as LPJmL continues to be developed, they are omitted from this analysis – only for reasons of comparison with other studies we present some global results including these crops as well). Each CFT represents irrigated and rainfed areas according to a modification of the MIRCA2000 land use dataset (Portmann et al., 2010, see Fader et al., 2010). Numerous studies have evaluated and validated LPJmL and its predecessor LPJ, most recently Bondeau et al. (2007) for crop yields and phenology, Fader et al. (2010) for yields and VWC, Gerten et al. (2004) and Biemans et al. (2009) for river discharge, Rost et al. (2008) for irrigation water requirements and Waha et al. (2011) for sowing dates.

4.2.2 Model setup and data

In order to bring the distribution of natural vegetation and the soil carbon pools in equilibrium, we carried out a spin-up simulation, for which the climate of the period 1901–1930 was repeated 30 times. Subsequently, we performed a transient model run for the study period 1998–2002, forced by monthly air temperature, precipitation and cloudiness (from the CRU TS3.0 database; http://badc.nerc.ac.uk/data/cru; last access: 10 December 2009), soil texture based on the FAO soil data set (as in Gerten et al., 2004), CO_2 concentration, and land use patterns as described above. As an improvement to the former model versions which considered two soil layers, this model version includes five soil layers with root distributions adapted from Jackson et al. (1996) (Sibyll Schaphoff, unpublished data). This development had little influence on the results of the present study as compared to the previous version documented in Fader et al. (2010), since VWC mainly depends on yields and since yields are calculated with calibrated management intensities (see section 4.3.1). LPJmL is run here at a spatial resolution of 30 arc-minutes globally and at a daily time step, with monthly climate data being interpolated to quasi-daily values as in Gerten et al. (2004).

Annual imports and exports of agricultural commodities were taken from the United Nation's COMTRADE database ("Commodity Trade Statistics Database", http://comtrade.un.org; last access: 7 July 2009) and averaged for the period 1998–2002. For the purpose of this study some commodities had to be reclassified so that they correspond to the CFTs: wheat, rye and barley were aggregated to the class of temperate cereals, sorghum and millet to tropical cereals, dry and fresh peas and beans to pulses, and sugar beets to temperate roots. Only raw commodity classes were used.

Population data for the year 2000 were taken from Grübler et al. (2007) (http://www.iiasa.ac.at/Research/GGI/DB), based on which per capita WFPs were calculated.

4.3 Computations of water flows

4.3.1 Green and blue virtual water content

LPJmL simulates water fluxes as described by Gerten et al. (2004) and Rost et al. (2008). Crop production and yields are simulated as described by Bondeau et al. (2007) and Fader et al. (2010) based on biophysical (including hydrological) conditions and management intensity, separately for irrigated and rainfed agriculture. In brief, CFT-specific sowing and harvesting dates are represented as a function of climate, allowing for simulation of shifts of the growing period in response to climatic variation and change. The sowing dates are calculated based on temperature and precipitation (Waha et al., 2011), photosynthesis is calculated following the Farquhar model (Sitch et al., 2003), and crop phenology and harvest dates are calculated based on the heat unit theory (see Bondeau et al., 2007 for details). LPJmL accounts for different, calibrated management intensities through three coupled parameters: the harvest index, the maximal achievable LAI and a parameter representing the heterogeneity of the fields (see Fader et al., 2010). It also accounts for the reduction of biomass and yields through water stress.

Irrigation is modelled to occur if soil moisture falls below 90% of the water holding capacity. This is also the case in flooded paddy rice areas that are classified as irrigation areas in the land use dataset. It is assumed that the CFTs' gross irrigation water requirements – computed from the ratio between atmospheric transpirational demand and soil moisture supply while considering country-scale irrigation efficiencies – can always be fulfilled (details in Rost et al., 2008). Interception loss from vegetation canopies (E_I) is considered a function of potential evapotranspiration (PET after Priestley–Taylor), canopy wetness, vegetation type and precipitation regime. Transpiration (E_T) is constrained either by PET (modulated by the boundary-layer state) or by soil water supply and plant hydraulic traits, with an additional influence of the vegetation's LAI and both physiological and structural effects of ambient CO_2 concentration (Gerten et al., 2007; Fader et al., 2010). Soil evaporation (E_S) is calculated as a function of PET, water content of the upper soil layer, daily phenological status and fractional area covered by a CFT. Total water consumption (evapotranspiration E) of a CFT is given by the CFT-specific sum of E_I, E_T and E_S. Note that we consider each of these components to have a green (GE) and a blue (BE) water constituent, such that for each CFT and day:

$$E = GE_I + BE_I + GE_T + BE_T + GE_S + BE_S \quad (1)$$

The separation into green and blue constituents relies in the case of E_I on the shares of irrigation water supply and precipitation on the field and in the case of E_T and E_S on the shares of blue and green water stocks in the soil (for the detailed calculation procedure see Rost et al., 2008). On rainfed areas E only consists of green water (i.e. BE = 0), whereas on irrigated areas, E consists of both GE and BE. Fig. 4.1 gives an overview of the computation procedure.

For each CFT blue (BVWC), green (GVWC) and total VWC (all in $m^3\ kg^{-1}$) were computed based on the CFT's yield and the three evapotranspiration components as follows.

$$BVWC = \frac{\frac{BE_{Irr}}{Y_{Irr}} * F_{Irr}}{F_{Ra} + F_{Irr}} \quad (2)$$

$$GVWC = \frac{\frac{GE_{Ra}}{Y_{Ra}} * F_{Ra} + \frac{GE_{Irr}}{Y_{Irr}} * F_{Irr}}{F_{Ra} + F_{Irr}} \quad (3)$$

$$VWC = BVWC + GVWC \quad (4)$$

where Y_{Ra} and Y_{Irr} are the CFT-specific yields (in g dry matter per m^2) of rainfed and irrigated areas, respectively. F_{Ra} (F_{Irr}) represents the rainfed (irrigated) fraction of the grid cell covered by the CFT.

4.3.2 Virtual water and land flows

As a first step to compute the virtual water flows and water footprints, BVWC, GVWC and VWC values were aggregated for each country using a weighted average of the individual grid cell's values accounting for the different areas of a CFT (rainfed and irrigated) and the absolute grid cell size. The thus derived values were then combined with the amount of agricultural commodities traded between countries (derived from COMTRADE).

The green and blue virtual water export from a country C was computed taking into account the national average CFT-specific values of BVWC and GVWC:

$$BVWE_C = \sum_{CFT=1}^{11} Ex_{C,CFT} * BVWC_{C,CFT} \quad (5)$$

$$GVWE_C = \sum_{CFT=1}^{11} Ex_{C,CFT} * GVWC_{C,CFT} \quad (6)$$

$$VWE_C = GVWE_C + BVWE_C \quad (7)$$

where Ex is the export (kg) of CFT products, being BVWE the blue, GVWE the green, and VWE the total virtual water export (all in m^3). (Note that due to the lack of data indicating which proportion of exports has actually been produced in C and which proportion represents re-exports from other countries, this study assumes that all exported commodities were produced in C. If COMTRADE indicates that C exports goods which are not produced in that country according to LPJmL and its underlying land use dataset, these exports are not taken into account. If COMTRADE indicates that C exports more than it produces according to LPJmL, the export amount is reduced to fit the simulated production.)

Analogous to the above calculations, the virtual water import of a country C was separated into a green and a blue share, taking into account the *ex situ*, CFT-specific values of BVWC and GVWC of each country i from which it receives the imported goods:

$$BVWI_C = \sum_{CFT=1}^{11} \sum_{i=1}^{n} Im_{C,CFT,i} * BVWC_{CFT,i} \quad (8)$$

$$GVWI_C = \sum_{CFT=1}^{11} \sum_{i=1}^{n} Im_{C,CFT,i} * GVWC_{CFT,i} \quad (9)$$

$$VWI_C = GVWI_C + BVWI_C \quad (10)$$

where Im are the imports to C (in kg), and BVWI, GVWI and VWI are the blue, green and total virtual water imports, respectively (all in m^3). VWI_C depends not only on the amount of commodities imported by C but also on the products' *ex situ* VWC of the countries i exporting to it. Analogously, VWE depends on both the amount of commodities exported by C and its *in situ* VWC values. High values of VWI and VWE can thus result from intensive trade flows, high VWC values, or a combination of both.

The net balance of country C for green (GVWB), blue (BVWB) and total (VWB) virtual water (in m^3) was calculated as:

$$BVWB_C = BVWI_C - BVWE_C \quad (11)$$

$$GVWB_C = GVWI_C - GVWE_C \quad (12)$$

$$VWB_C = GVWB_C + BVWB_C \quad (13)$$

Hence, negative values indicate that C is a net exporter of virtual water, and vice versa. Note that VWB depends on the imported and exported amount of commodities, the country-internal VWC, and the *ex situ* VWC of the countries i exporting to C.

In order to demonstrate the significance of the virtual water exports, we set VWE in relation to the country's current water consumption (E of the 11 CFTs considered here).

A combination of the CFT-specific average yield per country and its export/import amounts gives an idea of the land area that is used for producing the exported goods and the "virtual land" imported from other countries:

$$VLE_C = \sum_{CFT=1}^{11} \frac{Ex_{C,CFT}}{\overline{Y}_{C,CFT}} \quad (14)$$

$$VLI_C = \sum_{CFT=1}^{11} \sum_{i=1}^{n} \frac{Im_{C,CFT,i}}{\overline{Y}_{CFT,i}} \quad (15)$$

$$VLB_C = VLI_C - VLE_C \quad (16)$$

where VLE and VLI are the virtual land export and import, respectively, and VLB is the virtual land balance (all in ha). Negative values of VLB represent a net export of virtual land, while positive values represent a net import. To put into perspective the virtual land exports, we calculated for each country the ratio of VLE to the country's cropland area.

4.3.3 Internal and external green and blue water footprints

The internal water footprint of a country ($IWFP_C$) is the amount of water consumed (evapotranspired) in that country to produce the food consumed by its inhabitants (i.e. the total crop water consumption minus the virtual water export, see Eq. 17), assuming no changes in stock of agricultural commodities. Analogously, the external water footprint of a country ($EWFP_C$) is the water consumed in other countries to produce the food consumed in C. IWFP and EWFP – either in km^3 or m^3 cap^{-1}, depending on whether the footprint was computed per country or per person – both have a green and a blue component, respectively.

$$BIWFP_C = \frac{\sum_{CFT=1}^{11} (BE_{C,CFT} - BVWE_{C,CFT})}{Pop}$$

(17)

BIWFP is the blue internal water footprint, and Pop is here the population of C after Grübler et al. (2007). The green internal water footprint (GIWFP) was computed analogously. The total IWFP is the sum of BIWFP and GIWFP. The blue ($BEWFP_C$) and green external water footprints ($GEWFP_C$) equal the country's BVWI and GVWI, respectively (see Eq. 8 and 9), and they were also computed per capita. The total external water footprint EWFP is given by the sum of BEWFP and GEWFP.

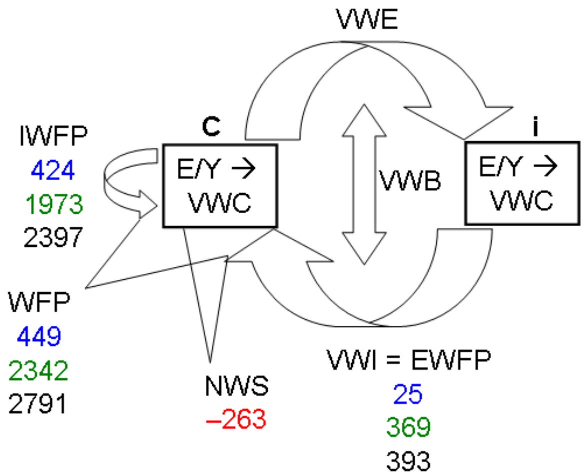

Figure 4.1: Overview of the water flows illustrated for countries C and i (see Methods) and total global values of blue (in blue), green (in green) and total (in black) water footprints as well as net water savings (in red). All values are in km³ and represent sums over the 11 CFTs included in this study averaged for the period 1998–2002. Note that the global VWE equals the global VWI, and that the global VWB is zero. Global water and land productivity are implicitly increased through trade by 8% and 5%, respectively (see Results).

Finally, the total blue water footprint (BWFP) of a country is the sum of BIWFP and BEWFP; the total green water footprint (GWFP) the sum of GIWFP and GEWFP; and the total water footprint (WFP) the sum of EWFP and IWFP or of BWFP and GWFP (Fig. 4.1).

By means of computing the absolute footprints (i.e. without the division by population), the total global green and blue agricultural water footprints were calculated as the sum of the national GWFP and BWFP values, respectively.

4.3.4 Water and land savings

By importing agricultural goods, a country 'saves' the water and land that it would have needed to produce them. Correspondingly, if a country would decide to avoid imports of agricultural goods (e.g. in order to reduce dependence on other countries or to promote inland agriculture), it would have to use own land and water for this production. We computed such savings as the amount of water (WS, green and blue combined, in m³) and the land area (LS, in ha) that a country would have needed to produce the imported crops on its own territory.

$$WS_C = \sum_{CFT=1}^{11} \sum_{i=1}^{n} Im_{C,CFT,i} * VWC_{C,CFT} \qquad (18)$$

$$LS_C = \sum_{CFT=1}^{11} \sum_{i=1}^{n} \frac{Im_{C,CFT,i}}{\overline{Y}_{C,CFT}} \qquad (19)$$

If the product analysed is not produced in the importing country, the CFT-specific global means for Y and VWC were used for the calculations. Note that the definition of water needs/savings WS differs from that of VWI (see Eq. 10), in that here the *in situ* VWC of the importing country C is used, while VWI is based on the *ex situ* VWC of the export country i.

Considering that, in turn, the agricultural areas cultivated for growing the exported products would be abandoned and left for natural vegetation or other non-cropland uses, we also quantified the water volumes (WR, in m³) and land areas (LR, in ha) that would be released this way as the amounts consumed for the production of exported goods. WR and LR equal the sum of virtual water and land exports from C (as computed by Eq. 7 and 14), respectively.

We furthermore subtracted the water and land savings from WR and LR, respectively:

$$NWS_C[m^3] = WR_C - WS_C \qquad (20)$$

$$NLS_C[ha] = LR_C - LS_C \qquad (21)$$

where NWS is the net water saving of country C (km³) and NLS its net land saving (ha). Negative values mean that the water or land that would be required for own production of imported goods is higher than the water or land that would be released in that country through avoided production of export goods, i.e. negative values imply net savings and positive values imply net losses through current trade.

Taking into account that Y and thus VWC vary strongly among countries, we also address the question whether globally the water and land resources that a world of self-sufficient countries would consume exceeds, or falls below, the resources consumed under current trade patterns. These global water and land savings or losses are represented by the sum of each country's net savings. Negative values of this global indicator suggest that producing the import goods in the own territories would consume globally more water/land than is the case under current trade patterns. We then related the countries' land/water savings and net savings to the current water consumption of the studied CFTs (E) and the (sowing) area they cover, respectively.

Finally, we investigated if the global water and land productivities (i.e. VWC and Y) were increased or decreased by international trade. This was done by comparing global estimates of VWC and Y in a world of self-sufficient countries and under current trade patterns.

4.4 Results

The following sections describe our results for virtual water contents, flows, footprints and savings as well as virtual land flows and savings. A detailed comparison of these results with previous studies can be found in Appendix 4.6.1.

4.4.1 Blue and green virtual water contents

As shown in Fig. 4.2, values of both BVWC and GVWC demonstrate a pronounced regional pattern. Especially GVWC is significantly higher across the southern hemisphere and large parts of Asia than in western and Central Europe and most of North America. While part of this regional discrepancy is attributable to differences in climatic and biophysical conditions, the main reason is differences in agricultural management intensity. As detailed in the study by Fader et al. (2010), VWC is high in poorly managed regions with low yields, whereas it is low in regions with favourable biophysical conditions and intensive agricultural management including irrigation. In most regions where irrigated and rainfed agriculture coexist, GVWC appears to be higher than BVWC, as vegetation grows faster and uses water more effectively in irrigated fields with continuous blue water supply; differences in sowing dates and phenological development also play a role. Similarly, both BVWC and GVWC also differ among coexisting CFTs (see Fader et al., 2010 for temperate cereals and maize). As discussed in Appendix 4.6.1, our values of BVWC and GVWC are in line with the few other estimates that are available.

4.4.2 Virtual water and land flows

As explained above, green and blue water need to be analysed separately due to different sources, opportunity costs, tradeoffs and environmental implications of their use. Thus, it is interesting to know if the traditional exporters/importers are trading mainly green or blue water, or if a country even has contrary balances depending on the type of water considered.

Figure 4.3a shows that the US, India, Thailand, China and Pakistan are significant net exporters of blue virtual water (negative value of BVWB). In contrast, countries such as Japan, Indonesia, North Korea and Bangladesh – and to a lesser extent also a number of countries in Europe, Africa and the Americas – turn out to be net importers of blue virtual water. As expected, rice imports and exports generally shape the blue virtual water balances.

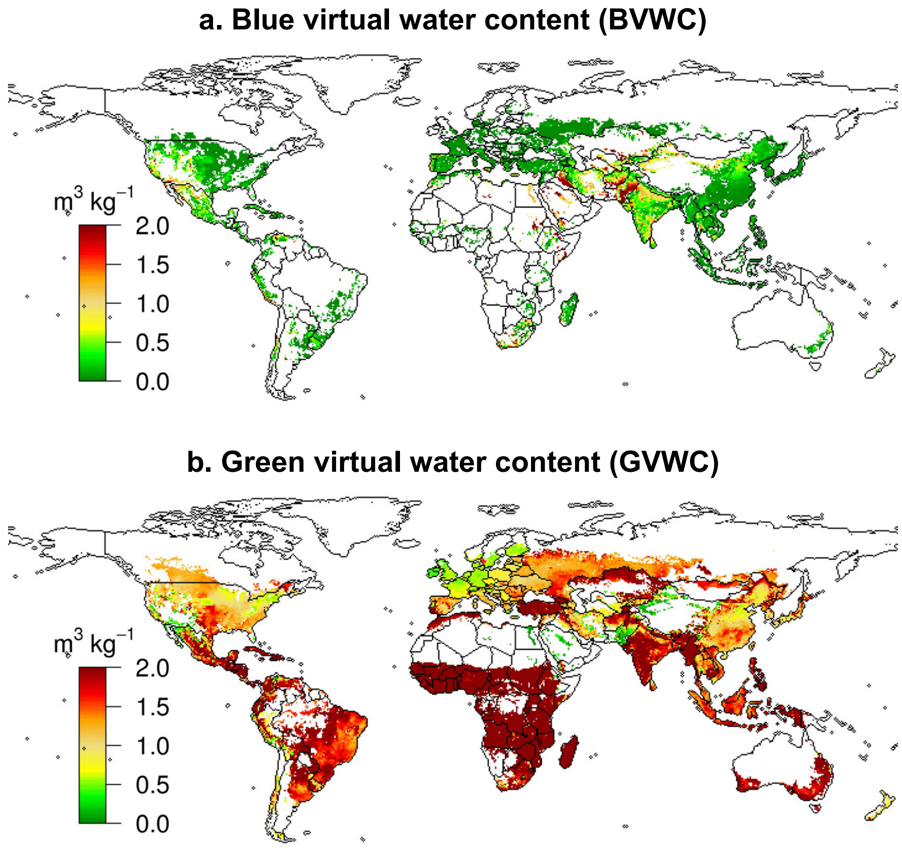

Figure 4.2: LPJmL-simulated blue (a.) and green (b.) virtual water content shown as average over all CFTs, 1998–2002 period and 0.5° resolution.

The US, Argentina, Australia, Canada and France are, according to our calculations for the considered CFTs, the countries with the highest negative balances of green water, mainly due to exports of wheat. Japan, Mexico, The Netherlands, North Korea and Spain are the largest net green virtual water importers (see Fig. 4.3b), basically due to imports of wheat, maize and soybeans.

Interestingly, Spain, Italy and China are net blue water exporters but net green water importers and Brazil is a net blue water importer but a net green water exporter.

The total virtual water balance (VWB) suggests that the US, Argentina, Australia, Canada and France are the largest net virtual water exporters of the CFTs considered here, whereas Japan, Mexico, North Korea, The Netherlands and Spain are the major net virtual water importers (see Table 4.1). While the net virtual water exporters export large quantities to many countries around the world, the net virtual water importers obtain the goods – thus the virtual water – mainly from the US, China, Argentina, Australia and Canada.

Paraguay, Argentina, Uruguay and Canada use more than 50% of their current (green and blue) water consumption to produce export goods; in the case of Australia, Cyprus and Oman it is more than 70% (data not shown).

Even if many net virtual water importers are water-scarce countries (compare UNEP, 2008 or Gerten et al., 2011, who show North Africa and large parts of Asia to be water-scarce, stressed or vulnerable), the top five net importers and others (such as the Andean countries) are characterized by a water availability of >2500 m^3 cap^{-1} yr^{-1}. Almost all net virtual water exporters appear to have abundant water resources, with the exception

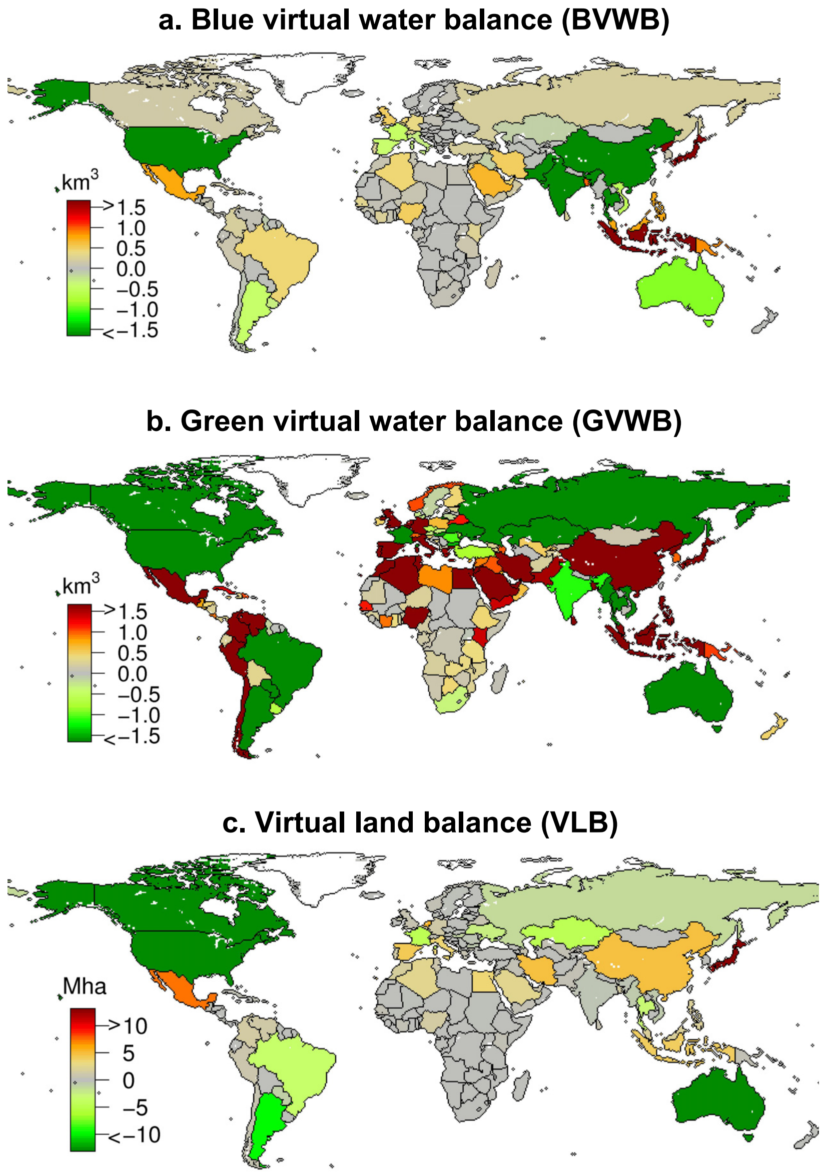

Figure 4.3: Countries' net virtual water and land balances for the 11 CFTs considered. Negative (positive) values indicate a net export (import) of virtual water or land. All values represent the means of the period 1998–2002.

of India, Pakistan and South Africa (UNEP, 2008). These results point out that VWB are frequently co-determined by factors other than water (Yang et al., 2003).

Concerning the VLB (Fig. 4.3c), i.e. the virtual land imports minus the virtual land exports, the US, Canada, Argentina and Australia are net virtual land exporters, while many countries in Southeast Asia and around the Mediterranean Sea are net virtual land importers. Guyana, Suriname, Cyprus, Australia, Luxemburg and Canada use >70% of their cropland to produce export goods (data not shown). Net virtual land exporters are in general large countries; however, not only the total area is relevant, but also the fertility of the soil and the slope. This could partly explain the fact that France and Thailand are net virtual land exporters, and China a net virtual land importer (compare maps on terrain slopes and soil resources from e.g. IIASA and FAO, 2000).

The patterns of VLB are very similar to the patterns in VWB; at country level

Pearson's correlation coefficient between both is 0.98. This demonstrates that virtual water flows are linked with virtual land flows; this is especially true for green water flows due to their correlation with the size of the area under cultivation. See Appendix 4.6.1 (and Table 4.A2) for a discussion of how our estimates of virtual land/water flows relate to other studies.

Table 4.1: Ranking of the top five net importers and net exporters for blue, green and total water.

Rank (descending)	
BLUE	
Japan Indonesia North Korea Bangladesh Papua New Guinea	Net Importers
United States India Thailand China Pakistan	Net Exporters
GREEN	
Japan Mexico Netherlands North Korea Spain	Net Importers
United States Argentina Australia Canada France	Net Exporters
TOTAL	
Japan Mexico North Korea Netherlands Spain	Net Importers
United States Argentina Australia Canada France	Net Exporters

4.4.3 Water footprints per country and per capita

The blue and green agricultural water footprints quantified here exhibit pronounced differences among countries. Also, there are substantial differences between (blue and green) internal and external water footprints, and they show a different pattern depending on whether they are calculated per country or per capita, as detailed in the following.

4.4.3.1 Internal, external and total blue water footprints

Figure 4.4 (top left) shows the total BWFP computed at country scale, i.e. the blue water evapotranspired in a country C for producing the 11 considered CFTs consumed in C and the blue water evapotranspired in other countries for producing the commodities exported to C. The map indicates that BWFP is highest (>30 up to 170 km^3) for India, China and Pakistan followed by the US (~20 km^3), and very low in Europe, South America and Africa. This pattern mainly reflects the BIWFP, as the blue external water footprint (BEWFP) is comparatively low (<1 m^3) in most countries (Fig. 4.4).

The aggregate global blue water footprint of the crop products considered here amounts to 449 km^3 (Fig. 4.1). Of these, only 25 km^3 are for exports, according to the low values of BEWFP. Note that this global agricultural BWFP is significantly lower than reported in earlier studies, as we consider only part of the cropland here. Including the collectively parameterised "other crops" would yield a global BWFP close to other estimates (923 km^3; see Appendix 4.6.1). Rice, temperate cereals and maize alone make up about 87% (390 km^3) of global BWFP in our study (data not shown). When computing the water footprints on a per capita basis, the spatial patterns differ significantly compared to those computed at country scale. Figure 4.B in Appendix 4.6.2 shows that the per capita total BWFP is highest in most countries in the Near East (up to ~300 m^3 cap^{-1}).

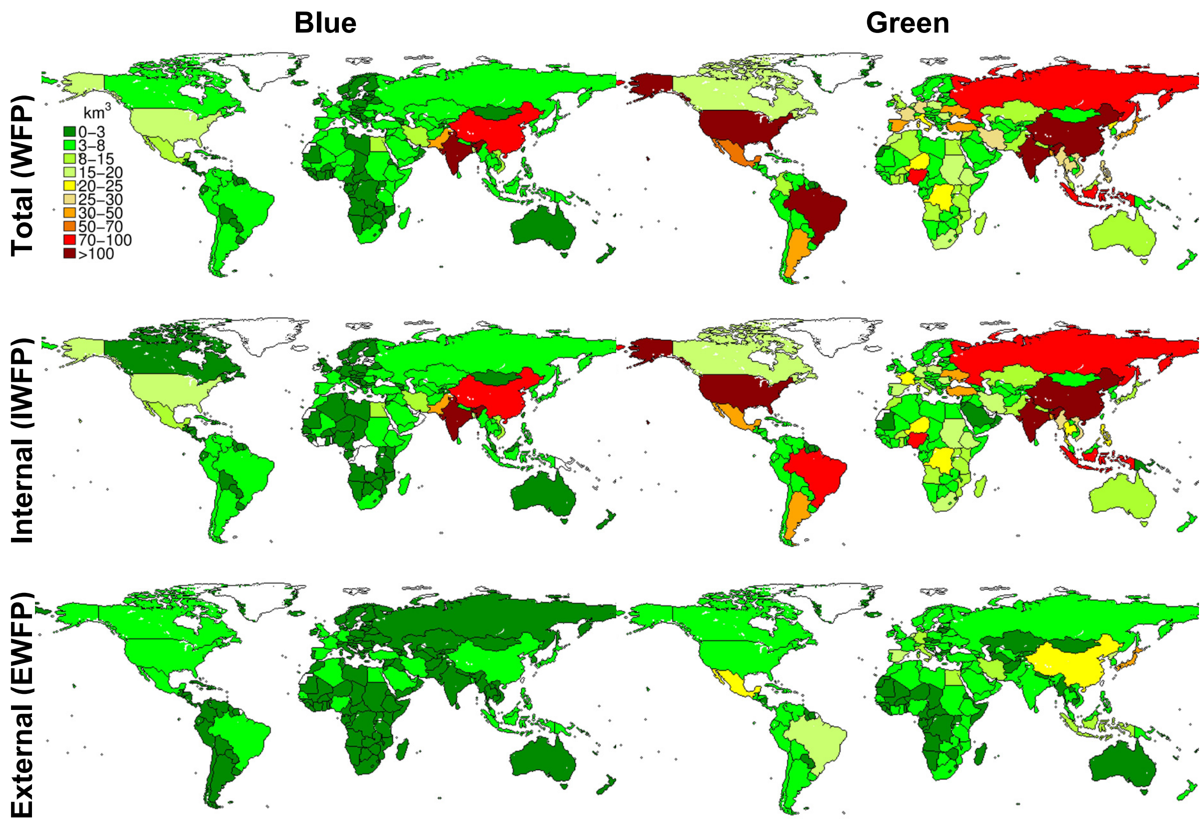

Figure 4.4: Internal, external and total blue and green water footprints per country for all CFTs, 1998–2002 average.

Countries such as Mexico, India, Pakistan and the US also show relatively high per capita values of BWFP, as in the case of the country-based values. Again, this pattern basically reflects that of BIWFP, while values of BEWFP are mostly very low, i.e. <30 m^3 cap^{-1} (Fig. 4.B), with notable exceptions of >100 m^3 cap^{-1} like for the United Arab Emirates, Papua New Guinea, and others.

4.4.3.2 Internal, external and total green water footprints

The total green water footprint of countries GWFP is highest (>100 up to 318 km^3) for China, India, the US and Brazil and lowest for many African and South American countries (Fig. 4.4, right panel). As in the case of blue water, this mainly reflects the pattern of the green internal water footprint GIWFP, though the external green water footprint (GEWFP) is also high for some countries, especially for Japan, Mexico, China and The Netherlands.

The global GWFP amounts to 2342 km^3 (including 369 km^3 for export goods, GEWFP; see Fig. 4.1), thus representing 84% of total crop water consumption. This percentage value confirms the estimates by Liu et al. (2009) and Liu and Yang (2010) for a similar sets of crops and the same time frame, but the absolute value is lower than found in earlier studies (Rost et al., 2008: 7242 km^3; Liu et al., 2009: 3103 km^3; Siebert and Döll, 2010: 5731 km^3; Hoff et al., 2010: 4975–5731 km^3). However, our estimate including the “other crops” yields 5978 km^3, which is of the same order than the above estimates. Maize, temperate cereals and rice are the main consumers of green water as in the case of blue water, but the contributions of tropical cereals, pulses and soybean are higher (data not shown; see Appendix 4.6.1 for some CFT-specific comparisons with other studies).

On a per capita basis, GWFP (and also GIWFP, see Fig. 4.B) exceed 1000 m^3 cap^{-1} in countries such as Niger, the Central African Republic and Argentina, and values are lower in many Andean and African countries as well as in China and India (Fig. 4.B). The GEWFP is generally lower than the GIWFP but relatively high (from 750 up to 1100 m^3 cap^{-1}) in the Netherlands, Cyprus, the United Arab Emirates and Israel.

Globally, both production and export of agricultural goods are dominated by green water: 84% of the global water consumption is green, and 94% of the total water used for the production of export goods is green, as many important exporters produce mainly under rainfed conditions.

The share of blue and green water consumed for export goods is relatively low (6% of the total blue water consumption is for export goods, and 16% of the total green water consumption is for export goods, Fig. 4.1). Only a couple of islands are shown to have a BEWFP to GEWFP ratio >1 (data not shown).

4.4.3.3 Linkages between high WFPs and EWFPs

In order to assess to what extent countries with high WFPs obtain virtual water from abroad, we related the external to internal WFP ratios to the WFPs per capita (see Fig. 4.5).

A total of 52 countries, including many countries in Europe, insular Asia and Africa, have a ratio BEWFP to BIWFP >1, meaning that they consume more blue water from abroad than from their own territory (quadrants II and IV). This is not due to the fact that a lot of them import high amounts of virtual blue water since most do not have BWFP per capita above average, with the exception of Lebanon, Malaysia and Switzerland. The reason is that the agriculture in these countries is based on green water, the consumption of own blue water thus being very low. This is also shown in the predominance of green colours in the quadrant IV (representing above average GWFP). Nevertheless, countries in the quadrants II and IV present to a certain degree a dependence on blue water imports.

Some Andean countries as well as countries around the Mediterranean Sea consume more green water from abroad than from their own resources, suggesting a certain dependence on green water imports (quadrants I and II). This is mainly due to low precipitation (i.e. lack of green water, partly also reflecting small cropland areas) as shown by the lack of green colours especially in quadrant I. The countries in quadrant II consume more blue *and* green water abroad than in the own territories, but not every one of them has WFPs above average.

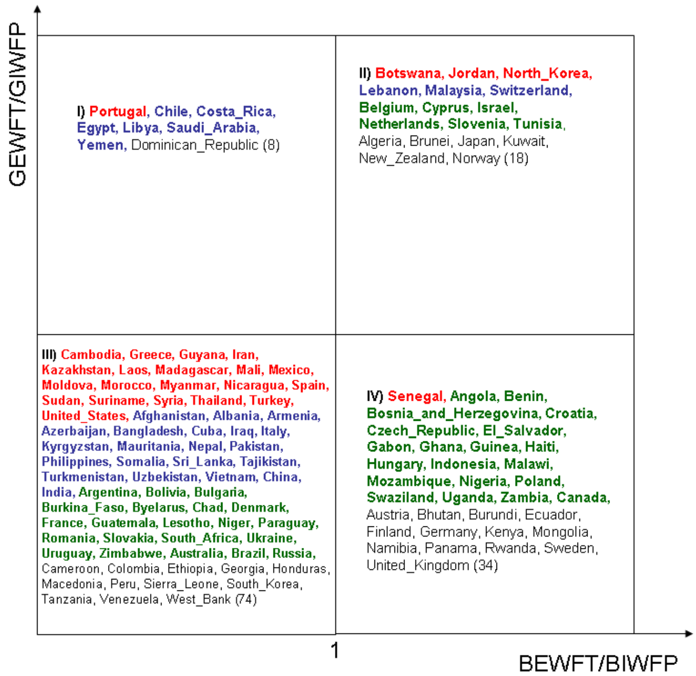

Figure 4.5: Classification of countries after their blue and green ratios of external to internal WFPs. Countries with values >1 on the x (y) axis consume more blue (green) water from other countries than from the own country. For countries coloured in red, BWFP *and* GWFP per capita exceed the respective global average; blue, only BWFP > global average BWFP; green, only GWFP > global average GWFP; black, BWFP and GWFP < respective global average. Numbers in parentheses at the end of the lists represent the total number of countries in the corresponding quadrant.

Most countries are in the quadrant III, indicating that they consume more green and blue water on the own territory than abroad. Nevertheless many of them present above average WFPs (green, blue or both).

In short: countries with high levels of per capita water consumption affect mainly the water availability in the own country.

4.4.4 Water and land savings related to trade

4.4.4.1 Water savings

As shown in Fig. 4.6a, some water-scarce countries, such as China and Mexico but also The Netherlands and Japan would need relatively high amounts of water to produce the goods they import, i.e. they save high amounts of water by importing goods (WS >25 up to 73 km^3). Putting these savings into the context of current green-blue water consumption (of the 11 CFTs) demonstrates that many countries – 39 in total, especially in North Africa and Latin America – would have to more than double their water consumption to produce their imports on the own territory (Fig. 4.6b).

The net water savings NWS (computed with Eq. (20) and shown in Fig. 4.6c) indicate that the US, Canada, Argentina and Australia would, as a net result, release water (up to 112 km^3) if they produced the imported agricultural goods on their own and did not export any goods. This means that these countries could hypothetically maintain the current consumption of agricultural goods and at the same time allocate part of the water used currently for the agricultural export sector to other uses, including natural ecosystems. The opposite is true for e.g. Japan, Mexico and The Netherlands (NWS<0). These countries would need to use more water (up to 72 km^3 in Japan) in their agricultural sectors if they stopped importing and exporting agricultural products. Overall, there are many more such countries with a negative NWS than countries with a positive one (162 vs. 23). Relating NWS to the current water consumption E reveals that some net exporters, such as Argentina, Canada and Australia, could allocate >50% of E for other purposes if there was no trade (Fig. 4.6d). By contrast, many net importers would have to strongly increase E.

Globally, current trade of the crop products considered here saves 263 km^3 of green and blue water (Fig. 4.1), or in other words, a world of self-sufficient countries under current consumption patterns would need this amount in addition to maintain the current levels of agricultural production/consumption. This amount represents ~0.2% of the global annual precipitation and 3.5% of the annual precipitation on cropland.

Water productivity at global level is 8% higher (i.e. VWC 8% lower) under current trade patterns than would be the case in a world of self-sufficient countries. However, the CFT-specific values were very different: pulses, temperate roots and groundnuts show values <1%, tropical roots, rapeseed, tropical cereals, rice and sunflower values between 1% and ≤5%, and temperate cereals, maize and soybeans values >9% up to 16%.

4.4.4.2 Land savings

Considering the land needed (LS) in order to produce imports goods on the own territory, i.e. the land saved for other uses, China and Mexico would need ~9 Mha, North Korea and The Netherlands ~7 Mha each, and Japan > 16 Mha (Fig. 4.7a). Relating these needs to the current cropland extent demonstrates that many countries – 40 in total, especially in North Africa and Latin America – would have to more than double the current cropland to produce their imports on the own territory (Fig. 4.7b).

The NLS as computed from Eq. (21), i.e. the additional land a country would have to use or the land a country would release for other uses in case of avoiding trade is shown in Fig. 4.7c. The patterns are very similar to the NWS (Fig. 4.6c), with e.g. North America, Argentina and Australia being able to release land (around 14 Mha for Australia

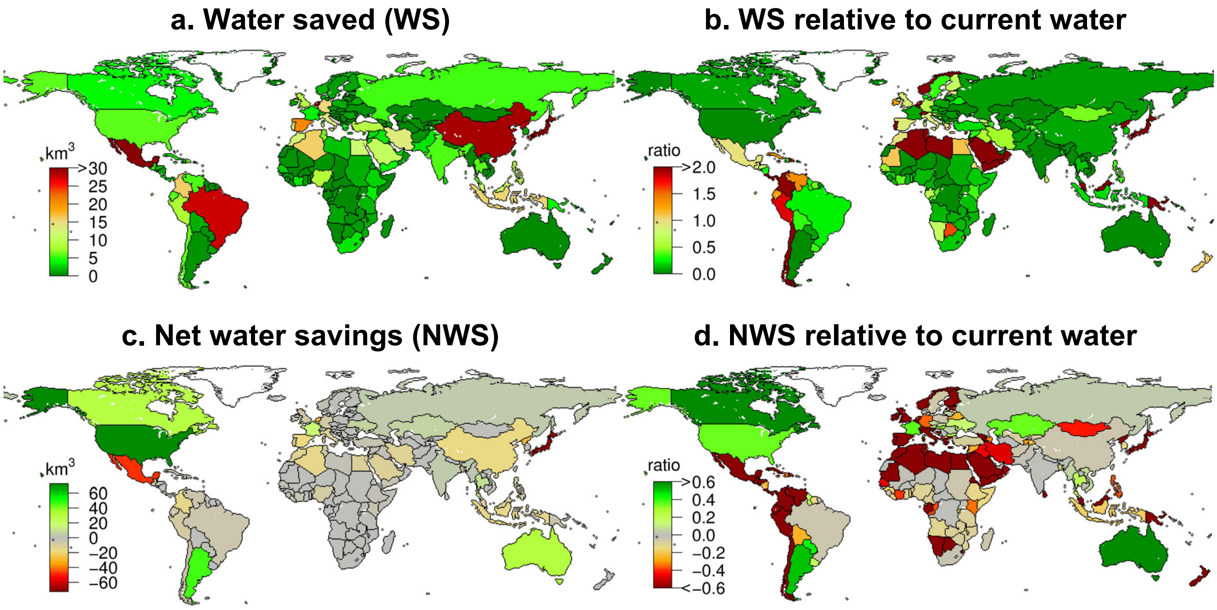

Figure 4.6: a. Green plus blue water volumes (WS in km^3) that would be required in a country's own territory for the production of imports (i.e. water saved through imports), **b.** WS relative to current water consumption E (values >1 indicate that own production of imports would need an amount of water more than double the present amount), **c.** net water savings NWS, i.e. WR–WS, and **d.** NWS relative to E. (Negative values in **c.** and **d.** indicate the need for consuming more water for crop production in case of no international trade).

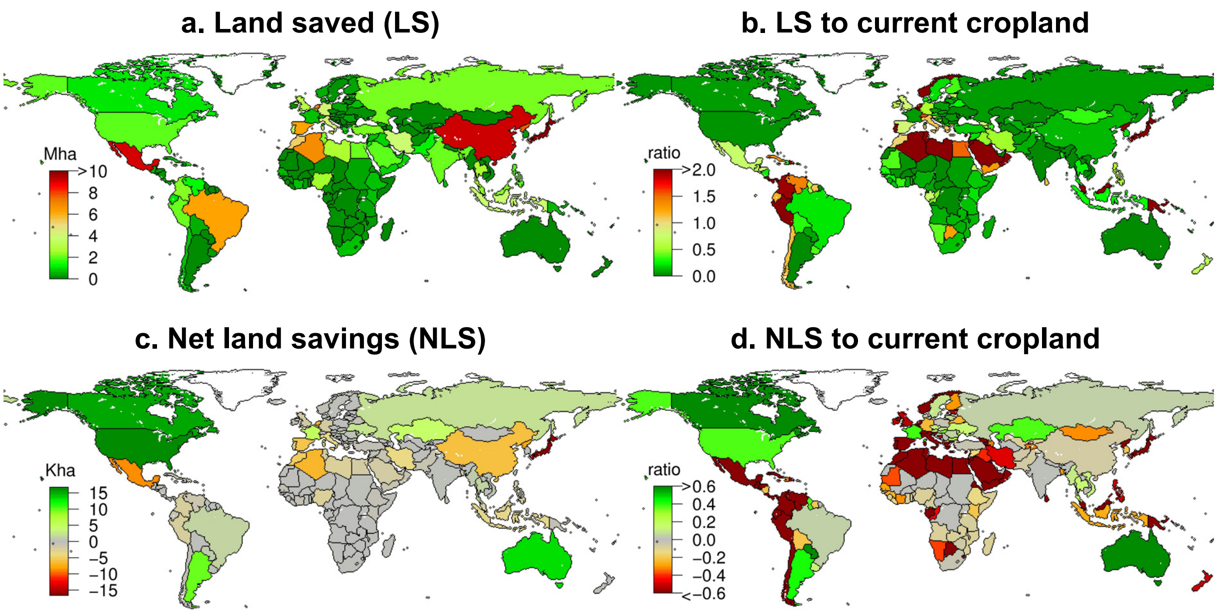

Figure 4.7: a. Land (LS, Mha) that would be required in a country's own territory for the production of imports (i.e. land saved through imports), **b.** LS relative to the current sowing area of the 11 CFTs in this study (values >1 indicate that own production of imports would need to use more than double the present cropland extent), **c.** net land savings NLS, i.e. LR–LS, and **d.** NLS relative to the current sowing area of the 11 CFTs in this study. (Negative values in **c.** and **d.** indicate the need for cropland expansion in case of no international trade).

and Canada and 35 Mha for the US) and parts of Africa and many countries in Europe, South America and Asia having to occupy additional land to produce what they currently import, e.g. 7–8 Mha for The Netherlands, North Korea and Mexico and 16 Mha for Japan (Fig. 4.7c). At country level the correlation coefficient between NWS and NLS is 0.96, suggesting that water savings/losses are associated with land savings /losses.

Relating NLS to the current cropland reveals that some net exporters, such as Paraguay, Canada and Australia, could allocate 60–70% of their current cropland for other purposes if they would not export any goods and produce the present imports on their own. On the contrary, many net importers would have to strongly expand their cropland (Fig. 4.7d).

Globally, current trade saves ~41 Mha (5% of the area presently occupied for the 11 CFTs considered), suggesting that a world of self-sufficient countries under current consumption patterns would need this land in addition to maintain the current levels of agricultural production/consumption. Current trade also leads to higher global land savings than water savings (at least when these are expressed as percentage of annual precipitation on cropland, see previous section).

Land productivity (i.e. Y) at global level is 5% higher under current trade patterns than it would be in a world of self-sufficient countries (CFT-specific values: tropical cereals, temperate roots, sunflowers and rapeseed <1%; temperate cereals, rice, pulses, tropical roots and groundnuts between 1% and ≤3%; soybeans and maize 16–17%).

4.5 Discussion

4.5.1 General findings

This study presents a process-detailed and spatially explicit differentiation of blue and green water in virtual water contents, virtual water flows and both country-internal and -external agricultural water footprints for the majority (though not all) of the world's crop types. The comprehensiveness of the study is innovative, since former studies were limited by the narrow list of commodities considered, the lack of differentiation (blue vs. green, internal vs. external) or some crude model assumptions (country-scale VWC calculations, neglect of water stress, no consideration of coexistence of crops in a grid cell – see Introduction). As a further novel aspect, it quantifies not only the water savings but also the land savings associated with the international trade of the respective crop products. Our main conclusions are as follows.

1) Green water dominates the production of agricultural goods, both for domestic consumption and for production of export goods: 84% of the total water consumption for the studied crops is from green water, and 94% of the external water footprint is constituted by its green water component.

2) Blue and green external water footprints are generally low (for the 11 CFTs, BEWFP = 6% of BWFP and GEWFP = 16% of GWFP).

3) No country ranks among the top ten with respect to *all* water footprints calculated here, but Pakistan and Iran have high absolute *and* per capita BWFPs, and the US and India high absolute GWFPs *and* BWFPs.

4) Countries with high WFPs per capita consume mainly water available on their territory (though part of the blue water can stem from upstream countries).

5) International trade globally saves both water and land (~263 km^3, ~41 Mha for the CFTs considered here).

6) Global water and land productivities are higher under current trade patterns than in a hypothetical world of self-sufficient countries (8% and 5% respectively).

7) Virtual land flows and savings are intrinsically related to virtual water flows

and savings, particularly in the case of green water.

In the following sections we will discuss these main findings, debate on relevant features of the model used, and suggest options for further research to complement and advance the present study.

4.5.2 Advances through dynamic and high-resolution crop and water modelling

As opposed to earlier studies of virtual water trade and water footprints, we employed a global vegetation and water balance model (LPJmL) simulating the dynamic interactions among water consumption (evapotranspiration and its components) in irrigated and rainfed agriculture (and also natural vegetation), the seasonal growth and productivity of different vegetation types under explicit consideration of water stress, and the associated carbon fluxes. Principally, we think that LPJmL can better account for effects of climate variability on crop production, yields and virtual water contents than stand-alone hydrological models (which usually do not represent crop dynamics at all) or models that use prescribed crop calendars (without accounting for short-term weather, particularly droughts). Apart from the comparisons presented herein (Appendix 4.6.1), we have carried out more detailed comparisons of LPJmL-simulated total VWC with available site-scale measurements and with estimates from other modelling studies for maize and temperate cereals (wheat) in Fader et al. (2010). In that study we also discussed the difficulties in validating such values given the absence of large-scale observations and the conceptual differences between models used for calculating VWC (and, based on this, VWE and VWI; see below). While the present comparison indicates quite robust results in that the *relative* differences between the different crop types are similar among the studies, systematic model intercomparisons are required to identify in detail the uncertainties related to model and data characteristics – including the sometimes very large differences in the underlying trade databases. A peculiarity with respect to trade data is that the lack of data concerning re-exports forced us to assume that the exports documented in the COMTRADE database were produced in the exporting country, which inevitably leads to biases in WFPs for countries with exports of goods not produced on their territory.

Of course, the model used here has shortcomings. For example, as in most if not all global hydrological studies, we had to assume that there always is enough blue water available for irrigation in regions equipped for doing so (see Rost et al., 2008). This may lead to an overestimation of blue water consumption and eventually blue water footprints for a few countries. If reliable global data on groundwater reservoirs were available, possible groundwater limitations could be represented better. Furthermore, agricultural management intensity (and the processes associated with it, such as fertilizer input, mechanization, pest and disease control, and soil conservation) is calibrated (Fader et al., 2010). This is a crude representation in need of improvement, but is in our opinion adequate for the present application, especially since we did not make projections for the future.

Obviously, it is an advancement to compute BVWC and GVWC at spatial units smaller than countries (here, 0.5° resolution) and at daily resolution using climate data for the particular grid cells (but see Liu et al., 2009; Liu and Yang, 2010; Mekonnen and Hoekstra, 2010a,b, 2011). Nevertheless, we note that exported goods are often produced in specific areas of a country only. Hence, averaging values of BVWC and GVWC over all CFT-specific production areas of a country – as done in this study – may produce somewhat biased estimates, especially in large countries with strong climatic gradients. Future studies should thus try to identify those areas within a country where the export goods are being produced, and should also account for sub-national virtual water flows.

4.5.3 Water footprints dominated by green water and country-internal consumption

Our analysis shows that green water consumption dominates production of agricultural goods both for own consumption and for export and that IWFP are mostly higher than EWFPs. Nevertheless, even little amounts of water consumption can be damaging or have alternative valuable uses, depending on the type of water (blue vs. green) and the local water scarcity situation. This is why future studies would have to relate the current consumption to the resource base, i.e. assess whether virtual water export aggravates water scarcity in the exporting country – see Pfister and Hellweg (2009) for an approach to weight footprints with water scarcity, and van Oel et al. (2009) for the relation between the Dutch EWFP and water scarcity in the trade partners.

Also, both green and blue water pools have different sources and opportunity costs – the costs of using water for other activities. Simply summing up both amounts makes the interpretation of WFPs difficult, if not useless. For example, Pakistan, Spain and India were shown to be blue water exporters, while many parts of these countries are usually classified by other studies as water-scarce regions (e.g. Vörösmarty et al., 2000; Gerten et al., 2011). Taking also into account that irrigation usually leads to environmental degradation (salinization, water logging, overexploitation of groundwater and surface water, etc., see e.g. Shiklomanov, 1997; Gleick, 2000) and considering that blue water has higher opportunity costs than green water, these countries are possibly making a suboptimal business in the long term by selling products produced with blue water at prices that mostly do not include externalities. On the other side, e.g. Indonesia and Brazil with their large BEWFP possibly contribute to environmental degradation in other countries by buying products produced under irrigated conditions. This is especially controversial when taking into account that both countries are not affected by water scarcity. Yet, many import countries have real constraints of resources to produce by themselves what they consume (e.g. land in Japan or water in the Middle East/North Africa region), and many economies of the export countries may collapse if they could not export any longer. For these reasons – even if isolated quantifications of the virtual water/land flows are useful for awareness-raising of the consumers – future studies should go a step further and link resources degradation caused by the export sector to different diets, including meat consumption.

This study is focused on agricultural goods for food, excluding industrial, livestock and household water consumption as well as some agricultural commodities such as cotton, tea and coffee. Due to the fact that only trade of raw agricultural commodities was included, some WFPs are probably over- or underestimated in net exporters or importers of processed crop products, respectively. The exclusion of industrial products should also affect only slightly our WFP estimates, since only 20% of virtual water flows correspond to non-agricultural products (Chapagain and Hoekstra, 2004). Considering the livestock sector, even if we excluded trade of cereal and seeds that were indicated to be for feed, this differentiation was not provided by COMTRADE for each country and for each commodity. Thus, especially countries with high meat consumption and importers of animal products certainly have overall WFPs higher than those presented here, and countries producing feed for animal products for export actually have lower WFPs than those presented here. For instance, the US and Australia export more than 25 km^3 of virtual water in livestock products, and Italy imports a similar amount; globally, the trade of rough and processed livestock products amounts to ~275 km^3 (Chapagain et al., 2004; Chapagain and Hoekstra, 2008; see also Hanasaki et al., 2010, for virtual exports of pork, beef and chicken).

4.5.4 Green water imports imply virtual land imports

This is to our knowledge the first study comparing the patterns of virtual land flows to virtual water flows, which is a step forward in the understanding of the joint human appropriation of water, land and biomass (see Haberl et al., 2007, on appropriation of photosynthesis products). Also, green water exports may be considered harmless from a water consumption point of view, since if a country would not export agricultural products and the export regions would be converted into natural vegetation, this vegetation would still consume the same or an even higher amount of green water than the agricultural plants. At the same time a country with a high GEWFP could use this argument not to think about its contribution to water scarcity in the exporting countries. These arguments were weakened in this study by demonstrating that green water exports are intrinsically linked to virtual land exports – and this land could have been used differently, e.g. for providing ecosystem services, as socially important recreation areas or as basis for other economic sectors, such as timber exploitation.

The virtual land flows presented in this study can be regarded as a component of the Ecological Footprint (EFP, the area that is needed to produce the resources consumed by a nation and absorb the waste it generates; e.g. Ewing et al., 2010). The EFP includes also the non-agricultural uses of land but omits accounting for water consumption. Moreover, EFPs give no quantitative information about the countries that are providing virtual land to others nor about the land saved by the net importers, as presented here. Thus, joining the information presented here with the EFP concept would give a more complete picture of the current human appropriation of natural resources (see Hoekstra, 2009a, for a methodological comparison of EFP and WFP).

4.5.5 Net savings of water and land through international agricultural trade

This study found that current trade saves significant amounts of green and blue water and land. Net exporters, such as Argentina and Australia, use a certain amount of domestic resources for the production of export goods, i.e. they "lose" resources through trade. On the contrary, net importers like Japan and Mexico "save" domestic water and land by importing goods that need water and land to be produced.

From the perspective of resources utilization, one could minimize land and water needed globally by reallocating production to countries with high land and water efficiencies. However, this would pose several challenges: a) Importers would increase their dependence on other countries; b) Many countries do not have the financial means to import the goods they would need and are already today involuntarily out of the virtual land and water market (Yang and Zehnder, 2007); c) Increasing imports, especially in countries with poorly developed rural infrastructure, could favour urban consumers, while putting pressure on the domestic agricultural sector, causing rural poverty and rural–urban migration (Yang et al., 2006); d) Increasing exports could lead to increasing deforestation and land and water contamination (Hoekstra, 2010), but this would certainly also be caused by increased domestic production in the hypothetical case of autarky; e) High water and land productivities are frequently linked to high input use (fertilizers, pesticides), potentially leading to high pollution rates if not properly regulated (Yang and Zehnder, 2007). These aspects highlight the need for regional studies in a global context, aiming for a deeper understanding of the possible ecological and social consequences of virtual water and land trade.

Furthermore, global water savings are based on the spatial differences in VWCs: if all countries would have the same VWCs, there would be no global water saving. This could lead to confusing concepts, e.g. in that a worsening in the VWCs of net importers would indicate higher global savings (and vice versa), although the absolute amount of water consumed in such a situation would be higher. This methodology also implies that the extra production needed domestically is achieved with current crop yields and water productivities. However, this may not be true in reality, since countries may promote either intensification of the domestic agricultural sector (leading to higher land and water productivities) or use of marginal areas (leading to lower land and water productivities).

Finally, climate change will modify the natural basis for food production (e.g. by extreme events, changes in precipitation and temperature, Solomon et al., 2007) and climate mitigation will probably restructure the energy sector, promoting the cultivation of biofuel crops (e.g. Lapola et al., 2009). This will lead to stronger land and water tradeoffs of food production and cause price increases, forcing the evaluation of virtual water/land trade as an adaptation option. Nevertheless, trade will probably keep being mainly determined by non-water related economic and political forces, such as relative prices and trade barriers (Yang et al., 2006).

4.6 Appendix

4.6.1 Comparison with other estimates

This appendix offers a detailed comparison of our results with previous estimates.

4.6.1.1 Blue and green virtual water contents

We compared values of BVWC and GVWC with the very few available studies that distinguished these two components. Dabrowski et al. (2008) calculated for maize in southern Africa slightly lower values of BVWC and GVWC than we did. However, they neglected water limitations, climatic differences within the countries and differences in irrigation efficiencies, which could have led to an underestimation of VWC.

Aldaya et al.'s (2008) model-based values for maize, soybeans and wheat for the four main exporting countries agree well with our estimates for GVWC but are generally higher for BVWC.

Hanasaki et al.'s (2010) results for the main exporters of rice, soybeans, wheat and maize are very similar to our estimates, except for BVWC of rice, where Hanasaki et al. (2010) have lower values.

Comparisons for a large number of countries and for wheat with the grid cell-based study by Mekonnen and Hoekstra (2010a) also yield a good agreement (average of differences at country level for BVWC<0.2 m^3 kg^{-1} and for GVWC<0.6 m^3 kg^{-1}).

In most cases Siebert and Döll (2010) calculated similar VWC for a larger number of crops with the GCWM model, except for BVWC of pulses (lower in this study) and sugar beets (higher in this study). Possible sources of differences to that study – which was based on similar land use datasets (based on Portmann et al., 2010) – are the method for the calculation of evapotranspiration (this study, Priestley–Taylor method; Siebert and Döll, 2010, Penman–Monteith method; see their study for discussion of this aspect), and the different treatment of growing periods (LPJmL, dynamic sowing and harvesting dates; GCWM, fixed growing periods from crop calendars).

During final preparation of this manuscript a report of Mekonnen and Hoekstra (2010b) was published with a lot of similarities to this study. A corresponding journal paper (Mekonnen and Hoekstra, 2011) is currently under discussion and review in HESS. We compared the results shown in the tables 3 and 4 of the report with our BVWC and GVWC and noted a good agreement, except for groundnuts (their estimate is much lower for BVWC) and cassava (their estimate is much lower for GVWC). Reasons for discrepancies could be the different time period (theirs 1996–2005) and differences in the preparation of the land use inputs.

4.6.1.2 Virtual water flows and water footprints

As can be seen in Table 4.A1, LPJmL-computed total VWE values compare well with those found by Chapagain and Hoekstra (2004, Appendix XIX). Oki and Kanae (2004) compute much higher values for temperate cereals and rice; one likely reason is that they assumed a constant global average crop water requirement and no differences between the growth stages. Our values for wheat compare well with the grid-based values found by Mekonnen and Hoekstra (2010a), while there are unsystematic differences between our values and those found by Hanasaki et al. (2010) – likely due to differences in the trade data used, since the agreement in VWC is quite good (see above).

The global BWFP (449 km^3) calculated in the present study is lower than the blue water consumption computed by Liu et al. (2009) with the GEPIC model (720 km^3) as they considered more crops (17 in total). Adding the water footprint of the collectively parameterized “other crops” so as to approximate the footprint of all crops, we obtain a blue water consumption of 923 km^3, which is almost equal to the value of GEPIC (927 km^3) reported in Hoff et al. (2010). This value is also comparable to the LPJmL-based study by Rost et al. 2008 (1258 km^3; the remaining difference is because that study was based on a different land use dataset with some differences in parameterizations, and no calibration of management was performed). A CFT-specific comparison with the values of Siebert and Döll (2010) also yields a very good agreement, even if LPJmL calculates lower values for temperate cereals and rice (Table 4.A1).

GWFP represent in our calculations 84% of total crop water consumption. This percentage value is very similar to the 81% found by Liu et al. (2009) and exactly the same as found by Liu and Yang (2010), in both cases for similar sets of crops and the same time frame, but the absolute value is lower than found in earlier studies (Rost et al., 2008: 7242 km^3; Liu et al., 2009: 3103 km^3; Siebert and Döll, 2010: 5731 km^3; Hoff et al., 2010: 4975–5731 km^3). However, an estimate for all crops including the “other crops” yields about 6000 km^3, which is of the same order than the above estimates.

The CFT-specific comparison of GWFP with the global values of Siebert and Döll (2010) yields a very good agreement, though LPJmL calculates lower values for temperate and tropical cereals, rice and soybeans (Table 4.A1). Compared with Hoekstra and Chapagain (2007b) – who, however, did neither consider climate variability within countries nor water stress – the agreement of CFT-specific WFP values is pretty good, except for rice and temperate cereals where their estimates are higher (data not shown).

4.6.1.3 Water savings

Comparison of WS with other estimates reveals a good agreement for maize and soybeans with Yang et al. (2006) and unsystematic differences with Oki and Kanae (2004) (Table 4.A1). Concerning NWS, the respective values of Yang et al. (2006) for soybeans are in good agreement but we obtained higher net water savings for maize and lower ones for temperate cereals (see Table 4.A1). While those authors calculated a positive NWS for rice, the present study calculated a negative one. Moreover, our global NWS is slightly lower than theirs (263 km^3 vs. 337 km^3). Differences can again be caused by different methods used to compute evapotranspiration (Penman–Monteith vs. Priestley–Taylor) and because Yang et al. (2006) used VWC computed by the model CROPWAT, which does not consider water stress even in rainfed agriculture and which

Table 4.A1: Comparison of VWE, WFP, WS and NWS with other estimates. All values in km^3. * From their table 8, for temperate cereals, sum of barley and wheat. § From their Appendix IX. & From their table 3, for temperate cereals only wheat. # From their Appendix XIX, only rough product categories used; for temperate cereals: sum of oats, rye, barley and wheat; for tropical cereals: sorghum and millet, for pulses: peas, chickpeas and lentils. + From their table 2; for temperate cereals, sum of wheat and barley; signs were inverted for NWS to make the numbers comparable with the present study.

CFT	BVWE			GVWE			VWE			BWFP		GWFP		WS			NWS		
	This study	Hanasaki et al. 2010*	Mekonnen and Hoekstra, 2010a§	This study	Hanasaki et al. 2010*	Mekonnen and Hoekstra, 2010a§	This study	Oki and Kanae, 2004&	Chapagain et al., 2004#	This study	Siebert et al., 2010	This study	Siebert et al., 2010	This study	Yang et al., 2006+	Oki and Kanae, 2004&	This study	Yang et al., 2006+	Oki and Kanae, 2004&
Temp.Cereals	4.61	16.40	7.78	151.90	127.30	174.69	156.51	270.90	129.05	126.91	220.30	572.77	834.75	229.01	373.9	464.20	-72.50	-150.4	-193.3
Rice	12.3	15.20		22.12	19.80		34.46	110.70	74.02	197.48	307.33	480.82	634.09	51.96	53.50	185.60	-17.50	10.10	-74.90
Maize	5.10	8.10		71.80	47.80		76.90	51.70	39.20	66.38	72.65	526.29	585.40	190.85	97.30	127.00	-113.9	-57.40	-75.30
Trop. Cereals	0.79			16.25			17.05		7.30	13.79	14.98	165.83	302.61	18.35			-1.30		
Pulses	0.48			15.27			15.75		7.83	12.71	22.99	129.91	173.22	17.24			-1.49		
Temp. Roots	0.05			0.15			0.19		0.20	5.09	9.14	21.80	19.82	0.19			0.01		
Trop. Roots	0.00			6.54			6.54		1.98	0.02	0.06	102.95	143.56	14.41			-7.87		
Sunflower	0.12			7.27			7.39		11.24	2.26	4.19	43.05	67.60	9.17			-1.78		
Soybeans	1.05	3.20		64.06	88.10		65.11	84.00	79.46	5.66	17.31	179.06	382.13	100.69	104.90	118.10	-35.58	-37.10	-34.10
Groundnuts	0.07			0.47			0.55		3.69	8.04	7.61	67.78	90.07	0.88			-0.33		
Rapeseed	0.01			12.88			12.89		16.15	10.21	7.99	51.86	51.06	24.00			-11.11		

Table 4.A2: Comparison of virtual land flows with other estimates. All values in Mha. * From their table 9, only data on VLI, for the year 2005. For temperate cereals we used their sum of wheat and barley, for tropical cereals the sum of millet and sorghum, and for pulses the sum of chicken peas, dry peas and dry beans. § From their figure 7, for 2007/2008.

CFT	VLI			VLE	
	This study	**van Sleen, 2005***	**von Witzke and Noleppa, 2010§**	**This study**	**von Witzke and Noleppa, 2010§**
Temperate Cereals	9.406	2.95	2.57	9.304	3.28
Rice	0.586	0	0.53	0.235	0.04
Maize	2.539	0.47	2.48	2.284	0.56
Tropical Cereals	0.401	0.1		0.095	
Pulses	1.470	1.57		0.494	
Temperate Roots	0.015	0		0.017	
Tropical Roots	0.894	0		0.000	
Sunflower	2.389	1.04		0.932	
Soybeans	8.650	4.92	19.24	0.061	1.71
Groundnuts	0.049	0.04		0.000	
Rapeseed	1.466	0.02		1.541	

was run at country level, using only the climate of the capital city.

De Fraiture et al. (2004) computed water savings for cereals similar to ours with the IMPACT model (276 km^3; LPJmL, 206 km^3), though they used a different time period (1995), different trade data and, as a whole, different modelling approaches.

Comparing NWS with Oki and Kanae (2004), the sign agrees for all crops considered and there is a very good agreement in the absolute values for soybeans, but unsystematic differences for other CFTs (Table 4.A1).

Chapagain et al. (2006) unfortunately do not provide CFT differentiated water savings, we thus could not compare our CFT estimates with that study. Their global estimate for what we called WS related to trade in crop products (i.e. the water needed to produce imports domestically) is 1286 km^3 (in our study 657 km^3), and for what we called NWS they computed 307 km^3 (our study 263 km^3). These numbers are however not directly comparable due to the differences in the list of commodities considered.

4.6.1.4 Virtual land flows

To our best knowledge, there are no studies on the global scale quantifying virtual land flows of agricultural goods, except for some estimates for certain regions and commodities; namely Steger (2005), van der Sleen (2005) and von Witzke and Noleppa (2010) computed virtual land flows from and to the European Union. Steger (2005), however, provided no crop-specific information, thus the comparison shown in Table 4.A2 contains only the remaining two studies. As can be seen, there are unsystematic discrepancies between all estimates, two possible sources are the different trade data used (this study, COMTRADE; van Sleen, 2005, WATM; von Witzke and Noleppa, 2010, EUROSTAT) and the various period of time considered.

We compared the net importing and exporting countries (Map 7 in Ewing et al., 2010) with our VLB and found clear similarities in the spatial patterns, with some exceptions: France and India are net importers in Ewing et al. (2010), while we calculate a net export from those countries, and the Philippines, Mexico and some Andean countries are net exporters in Ewing et al. (2010), while we calculate a net import.

The differences could be due to the fact that we only consider agricultural goods, while EFPs are calculated considering also industrial products and waste assimilation.

4.6.2 External, internal and total WFP per capita

See sections 4.3.1 and 4.3.2 for explanation of the Figure 4.B provided here.

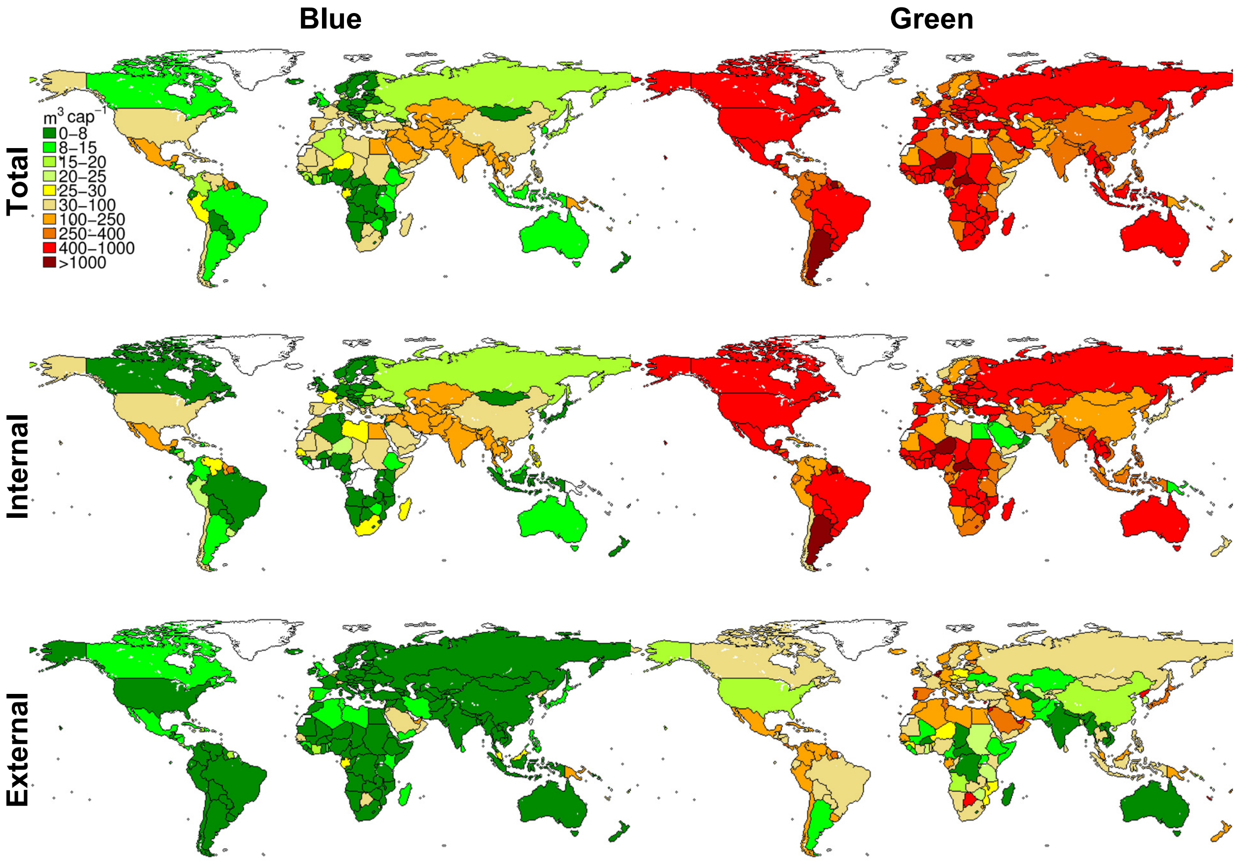

Figure 4.B: External, internal and total blue and green water footprints per capita for all 11 CFTs, 1998–2002 average.

Acronyms (alphabetically)

- BE, GE, E – Blue, Green and Total Evapotranspiration (interception, evaporation and transpiration)
- BEWFP, GEWFP, EWFP – Blue, Green and Total External Water Footprint
- BIWFP, GIWFP, IWFP – Blue, Green and Total Internal Water Footprint
- BVWB, GVWB, VWB – Blue, Green and Total Virtual Water Balance
- BVWC, GVWC, VWC – Blue, Green and Total Virtual Water Content
- BVWE, GVWE, VWE – Blue, Green and Total Virtual Water Export
- BVWI, GVWI, VWI – Blue, Green and Total Virtual Water Import
- BWFP, GWFP – Blue and Green Water Footprint (internal and external)
- CFT – Crop Functional Type
- E_I, E_T, E_S – Interception, Transpiration, Evaporation
- Ex – Exports
- Im – Imports
- LR – Land Released
- LS – Land Saving
- NLS – Net Land Saving
- NWS – Net Water Saving
- Pop – Population
- VLB – Virtual Land Balance
- VLE – Virtual Land Exported
- VLI – Virtual Land Imported
- VWF – Virtual Water Flow
- WFP – Water footprint (external and internal, blue and green)
- WR – Water Released
- WS – Water Saving
- Y_{Irr}, Y_{Ra}, Y – Irrigated Yield, Rainfed Yield, Total Yield

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Chapter 5

Dependence of countries on food imports due to limitations in domestically available land and water resources[4]

Marianela Fader, Dieter Gerten, Michael Krause, Wolfgang Lucht, Wolfgang Cramer

Abstract

In our globalising world, the geographical locations of food production and consumption are becoming increasingly disconnected. Many countries and their inhabitants rely on virtual land and water trade, i.e. on the land, water and biomass appropriated in those countries from which they import agricultural and other goods. One way of looking at this situation is through a quantification of 'footprints'. This study, however, quantifies to what extent water and land constraints limit countries' capacity to produce on their own territory the crop products (confined here to 11 major crop types) that they currently import from other countries. Rather than as a real priority for governments, this self-sufficiency is understood here as an analytical lens for assessing the dimension of countries' dependence on *ex situ* land and water resources now and in the future. To account for possible changes in management, land use and demography, we defined a set of scenarios considering country-specific increases in agricultural productivity, cropland expansion (constrained by availability and competing land uses), increased water use, and population projections (for around 2090, SRES A2r).

We found that presently 15% of the world population (900 million people) depend on land and water resources not situated in their home countries (often >50% of the population of North African, Arabic and Andean countries). If the full potential for cropland expansion were exploited in each country, 5% of the current world population would still depend on *ex situ* land resources (mostly in Japan, Algeria, Iran and Mexico). Population change by 2090 will strongly increase the number of people depending on *ex situ* land and water resources up to 7400 million (60% of world population). Even expanding cropland to its maximum availability in each country and increasing agricultural productivity in each country would

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leave 15% of world population dependent on virtual land imports by 2090, mainly in Africa and the Arabic peninsula.

5.1 Introduction

Urbanization and globalization are among the causes of an increasing geographical de-coupling between areas of agricultural production and consumption. The food of millions of people is being produced with land and water resources situated in countries that are sometimes thousands of kilometres away from their homes. For example, external water footprints for agricultural products (the amount of water used in export countries to produce products consumed in an import country) were shown to exceed 30 km^3 in China, Mexico and Japan, respectively (Chapagain and Hoekstra, 2006), and "virtual land imports" of more than 5 Mha were calculated for countries such as The Netherlands and North Korea (Fader et al., 2011). This implies a significant dependence of consuming countries on the political, environmental, demographic and economic situations of the exporting countries that might, more or less suddenly, decide to change or be forced to adapt the supply available to the market (in 2010, for example, Russia imposed a ban on wheat exports due to drought and wild fires, Graves, 2010). This threat became especially clear during the food crises 2007-2008, when a food price spike led to government-imposed bans on exports (e.g., in Brazil, Olle, 2008; and India, BBC News, 2008) and led to importers, for some of which the imports were quite critical, suffering a lack of supply (e.g. in Burkina Faso; Polovinkin, 2010). Such events can be regarded in some cases as a substantial risk to national food security. The extent of this risk depends on resource availability in the affected importing countries such as on their potential to increase domestic productivity in order to cope with international supply shortages.

Expected future developments such as climate change and population growth will put additional concurrent pressure on agricultural production. For example, productivity increases could fall short of the increased demand caused by population growth (Southgate, 2009) and it is expected that even slight warming in low-latitude and seasonally dry areas could have negative impacts on yields (Bates et al., 2008). Satisfactory adaptation measures will only be possible through knowledge about the potentials and limitations of the natural resources of each country and the degree of dependence on external resources.

A number of recent studies have provided information on particular countries' potentials for land and water productivity increases and interpreted these in terms of their dependence on other countries. Apparently, a number of countries may lose their capacity to produce the crop and livestock products on present cropland and grazing land due to limited per capita water availability in the future (as driven primarily by increased demand due to population growth) (Gerten et al., 2011). Linked to this, 36% of the world population could be living in countries not able to be self-sufficient in terms of food production by 2050 (Rockström et al., 2009). Other methods yielded 55% of the world's population depending on food imports by 2025 (Falkenmark, 1997). It is hence likely that feeding humanity and alleviating hunger by 2050 require a cropland expansion of ~0.8% yr^{-1}, even considering potentials for yield growth and water productivity increases (Rockström et al, 2007). Thus, the number of people living in regions unable to produce enough food on current croplands and where the import potential may be limited by weak national wealth level could reach 3.8-4.2 billion by 2050 (Falkenmark, 2009).

These studies do not consider actual, country-specific consumption of crop products. They work with nutritional requirements derived for a balanced diet (3000 kcal per capita and day for all people).

It is, however, a fact that most people do not eat what they nutritionally need; quantity and type of consumption is rather linked to culture, income, socioeconomic conditions, fashions and other factors (e.g. Wang, 2001; Hesse-Biber, 2006). For this reason, the present study is focused on present diet composition (restricted to the share of major crop products of these diets). Earlier studies also mostly did not consider country-specific resource availabilities and management regimes. For instance, Falkenmark (1997) estimated water requirements for food, households and industry on the basis of globally constant per capita requirements; water productivity increases in Rockström et al. (2007) and Falkenmark et al. (2009) were assumed to range from 1,300 m^3 cap^{-1} yr^{-1} to 1,000 m^3 cap^{-1} yr^{-1}, irrespective of the geographical conditions and current productivity levels.

These studies also assumed that agricultural management regimes and cropland extent will remain unchanged in the future, and they did not take into account that (agricultural) products are not necessarily produced in the same country where they are consumed, i.e. international trade was omitted.

Other studies have dealt with countries' dependence on external resources more explicitly. Using the ratios between external water footprint to total (sum of country-external and -internal) water footprint and external renewable water resources to total renewable water resources in order to define water dependence of countries, Egypt, The Netherlands, Jordan and the UK, among others, were found to be highly dependent on water resources in other countries (Hoekstra, 2009b). However, land resources, population growth and potential productivity increases were not accounted for. Considering land resources when defining dependence is important in this context, as Kumar and Singh (2005), Wichelns (2010) and Fader et al. (2011) have recently pointed out. Other authors calculated self-sufficiency ratios by dividing imports or domestic production by total consumption in mass, calories or economic units. Following such an approach, Japan (Honma et al., 2000), South Asia (Chand, 2006) and the Gulf States (Kotilaine, 2010) were presented as highly dependent regions. These studies, however, used static indicators that do not consider natural resources availabilities (sometimes completely uncorrelated with international trade), population growth and potential productivity increases.

The present study aims to contribute to this discussion by analysing global-scale water and land constraints for national food self-sufficiency (provisionally restricted to 11 major crops due to model and data constraints). Calculations are made for the present situation as well as for three scenarios of future agricultural productivity, while considering population change and environmental potentials for cropland expansion and increases in water consumption. Food self-sufficiency is a desirable objective for many countries striving to avoid dependence, to promote their domestic agricultural sector, to reduce rural poverty and avoid negative effects of global price fluctuations (e.g. Chand, 2006; World Water Council, 2004). Also, many environmental organisations promote local consumption of food, e.g. for reducing emissions from transport (Baker, 2008). Nevertheless, rather than as a real priority, self-sufficiency is understood in this paper as an analytical lens for assessing the extent of dependence of a country on other countries' land and water resources. This will provide a clearer understanding of potential global lock-ins that have developed through agricultural globalization, urbanization and technization.

Building on the work by Fader et al. (2011) – who quantified water and land savings through international trade of 11 major crops with the vegetation and hydrology model LPJmL and based on trade data from the COMTRADE database – we performed simulations to estimate water availability as well as crop production and yields assuming increases in agricultural productivities and future population change. We also estimated the area that could potentially be taken under crop cultivation, as derived from various data sources given different assumptions about trade-offs with other land uses. The objective of this study is to answer the following research questions:

a) How much domestic freshwater and arable land would countries have to appropriate in order to produce on their own territory the majority of the crops they currently import?

b) Could countries actually meet self-sufficiency, given their remaining available arable land and presently unused renewable water resources? That is, how dependent is each country on *ex situ* land and water resources even with expanded domestic production?

c) To what extent could better agricultural management (as an alternative to cropland expansion and increased water consumption) contribute to meeting these requirements, i.e. ease the dependence?

d) How would these dependence change quantitatively given population change by 2090?

5.2 Methods and data

5.2.1 LPJmL model

This study is based primarily on biogeochemical simulations with the dynamic global vegetation and water balance model LPJmL (Bondeau et al., 2007; Rost et al., 2008). The model calculates (at a daily time steps and on a global 0.5 grid) key ecological, hydrological and biogeochemical processes governing the growth of natural and agricultural terrestrial vegetation.

The inputs to the model consist of monthly climate data (here, CRU TS3.0 database; http://badc.nerc.ac.uk/data/cru; last access: 10 December 2009), annual CO_2 concentrations, soil texture (as in Gerten et al., 2004) and land use patterns (irrigated and rainfed areas as in Fader et al., 2010). Based on these, seasonal phenology (sowing and harvest dates, leaf status) and agricultural yields are simulated for 11 crop functional types (CFTs: temperate cereals, maize, rice, tropical cereals, temperate roots, tropical roots, rapeseed, groundnuts, soybeans, pulses, sunflower) and an additional category of “other crops” in which potatoes, sugar cane, oil palm, citrus, date palm, grapes, cotton, cocoa, coffee and others are provisionally treated as managed grassland.

In LPJmL, agricultural management is represented by three coupled, CFT-specific parameters, the maximal achievable leaf area index (LAI_{max}), the harvest index and a parameter indicating the degree of heterogeneity of the fields. Together they characterize a group of management effects, including varieties, nutrient supply and the degree of weed, pest and diseases control. In a calibration process, values of LAI_{max} are sequentially varied from one to seven for each CFT. The value with the best match to FAO yields (average of rainfed and irrigated) is chosen for each CFT and country (see Fader et al., 2010 for more details).

LPJmL simulates various hydrological variables ecophysiologically coupled with vegetation dynamics, including crop water consumption, irrigation requirements and crop water stress (see more details in Gerten et al., 2004; Rost et al., 2008).

5.2.2 Scenarios

In order to quantify the ability of each country to produce with their own land and water resources the CFT products otherwise imported from other countries, we defined three scenarios:

CUR: Countries are expected to produce the amount of current imports plus the domestic production minus the current exports. Crop yields, production and water consumption are calculated assuming present management intensities (LAI_{max} values as described above).

POT: Same as CUR, but yields and water consumption are calculated assuming optimal crop management countrywide. This is implemented by the use of the CFT-specific LAI_{max} value leading to the highest national yields (average of rainfed and irrigated).

HIG: Same as POT, but assuming a lesser improvement of agricultural management. This is implemented by the use of an LAI_{max} value of two units nearer to the one chosen for POT (or less units if the difference is smaller than two).

We furthermore analysed another set of these scenarios, in which we considered the magnitude of population in the year 2090, reaching a global number of 12.1 billion (SRES, A2r, Grübler et al., 2007, http://www.iiasa.ac.at/Research/GGI/DB; last access: 21 May 2010). For these calculations it was simply assumed that the desired crop production changes linearly with population, which implies unchanged diets.

For all scenarios, binational trade data for the 11 major crops considered in this study, averaged for the period 1998-2002, were taken from the United Nation's Commodity Trade Statistics Database (http://comtrade.un.org; last access: 7 July 2009). Note that trade and production of the LPJmL categories "other crops" and "managed grasslands" (basically representing the livestock sector) were not taken into account; but, importantly, their growing areas and their blue water consumption were considered when calculating available water and land resources (see sections 5.2.3 and 5.2.4).

The globally averaged productivity increases in HIG and POT are comparable with other estimates and thus, can be regarded as reasonable: HIG = 54% production increase in total, or an average of 0.5% yr^{-1} (range: 0.3-0.7% yr^{-1} depending on the CFT); POT = 109% production increase in total, or an average of 0.8% yr^{-1} (range: 0.3-1.2% yr^{-1} depending on the CFT); FAO (2002) = 0.6-1.7% yr^{-1}, Lotze-Campen et al. (2010) = 1-1.4% yr^{-1}).

For each of these scenarios, we assessed the water- and land-related potentials and limitations of each country to reach the specified crop production. For this, we calculated the ratio between the respective water and land requirements and the actual water and land availabilities as explained in the following sections. Based on that, we calculated the population fraction dependent on external resources globally and for each country.

5.2.3 Computation of countries' availability of renewable water resources

Countries' renewable water resources (RWR) were calculated in the LPJmL model as the sum of surface and subsurface runoff, water stored in aquifers, lakes and reservoirs and inflow of discharge from other countries, as an annual average for the period 1970-2000 given the land use pattern of around the year 2000. Fossil (i.e. non-renewable) groundwater was excluded.

In order to estimate the amount of RWR that is currently available and, thus, could be used for irrigated agriculture, we subtracted the current municipal and industrial water consumption at country level as reported by FAO (2003) for the year 2000. We also subtracted the irrigation water that is used currently for agriculture, i.e. the sum of blue water evaporation, transpiration and interception during the growing periods of the 11 CFTs and the "other crops". Moreover, it was assumed that 30% of RWR (see Smakhtin, 2004) need to be reserved for the functioning of ecosystems, i.e. as environmental flows; thus, this amount was subtracted at country level from RWR. The result of these calculations is referred to herein as available renewable water resources (ARWR). ARWR can become negative if a country makes use of non-renewable water resources, in this case it was set to zero.

5.2.4 Definition of countries' availability of land for cropland expansion

In order to determine the area available for potential conversion to cropland in each country (AL), we subtracted from the total area of each country the following areas: urban land; land used for forestry production; unproductive, unused land (production <20 gC m^{-2}); least productive grazing land (production between 20 and 200 gC m^{-2}) (all from Erb et al., 2007); total cropland (i.e. sowing area of the 11 CFTs and "other crops" considered in LPJmL); managed grassland (both from Fader et al., 2010); protected areas (IUCN classes I and II, from UNEP-WCMC, 2007); and areas worthy of protection (the union of Greenpeace's Intact forest landscapes and WRI's frontier forest, see Greenpeace International, 2005; Bryant et al., 1997). All data except for total cropland and managed grasslands were prepared, harmonized and corrected by Krause et al. (submitted).

Global values of ARWR and AL are 32439 km^3 and 1322 Mha, respectively (for the spatial patterns see Fig. 5.A1, right panel and Fig. 5.B1, lower, left panel). In sensitivity analyses we showed that our main results would not differ significantly if other estimates of ARWR and AL were used (see Appendix 5.A and 5.B).

5.2.5 Calculation of required cropland expansion and increase in water consumption

For the CUR scenario we calculated the required water consumption increase (WCI) as percentage of the available, renewable water resources of the country and the required cropland expansion (CE) as percentage of the available, productive land:

$$CE = \frac{NLS*(-1)}{AL}*100 \tag{1}$$

$$WCI = \frac{NWS*(-1)}{ARWR}*100 \tag{2}$$

where net water and land savings (NWS, NLS) are the amount of land and water that a country 'saves' or 'loses' through trade, or the other way around, the amount of water that it would need or release if it would not trade (no imports, no exports). NWS, as defined by Eq. 20 in Fader et al. (2011), is computed as the volume of virtual water currently exported minus the water that would be needed to produce import goods. Analogously, NLS is computed as the virtual land currently exported minus the land that would be needed to produce import goods (see Eq. 21 of Fader et al., 2011). The sign of the balances are inverted due to the fact that a negative balance would mean a needed increase in sowing area or water consumption.

If CE or WCI < 0, no cropland expansion or water consumption increases would be needed to reach a self-sufficient production. Positive values of CE and WCI indicate the proportion of the available resource that would have to be used. If CE or WCI > 100%, the country would not have enough available land and water to fulfil the production requirements in CUR.

For the POT and HIG scenarios, the following calculation was performed for each country:

$$CE = \frac{\sum_{CFT=1}^{11} \frac{P_{CFT,Exp} - P_{CFT,act}}{\overline{Y}_{CFT,act}}}{AL}*100 \tag{3}$$

where P_{Exp} is the production expected in each scenario (depending on the population considered: 2000 or 2090), P_{act} is the actual production in HIG or POT and $\overline{Y}_{act}$ is the average (rainfed, irrigated) yield of HIG or POT.

Note that CE can become negative should the productivity increases allow for a reduction of land under cultivation. In this case, we set CE to zero.

The water consumption increase in HIG and POT was calculated as:

$$WCI = 100 * \frac{\sum_{CFT=1}^{11} E_{CFT,act} + (P_{CFT,Exp} - P_{CFT,act}) * \overline{VWC}_{CFT,act} - E_{CFT}}{ARWR}$$
(4)

where E is the water consumption in CUR as the sum of transpiration, evaporation and interception loss during the growing period of the 11 CFTs. E_{act} is the water consumption in HIG or POT. $\overline{VWC}_{act}$ is the average (rainfed, irrigated) virtual water content of the analysed country in HIG or POT (VWC is the amount of water needed to produce a unit of crop; Fader et al. 2010). In the case that the productivity increases would allow for reduction of water consumption (WCI<0), we set WCI to zero.

The nominators of Eq. 1, 2, 3 and 4 represent CE and WCI in absolute terms (ha and m^3).

5.2.6 Number of people dependent on external resources

For assessing the number of people whose food is produced with land and water resources situated outside their countries, we first calculated the land and water requirements per capita as the sum of the requirements to replace imports and the requirements for maintaining the part of the production consumed domestically divided by the total population (per capita requirements are the same in 2000 and 2090 since we assume no change in diets). After that, we divided the absolute cropland expansion and water consumption increases in each scenario by the per capita requirements, obtaining the amount of people affected in each case. See details of this calculation in Appendix 5.C.

5.3 Results

5.3.1 Cropland expansion and water consumption increases for population of 2000

Given current crop productivities (CUR), 139 out of a total of 197 countries would have to expand their current cropland and 145 countries would have to increase their water consumption if they decided to produce the crops that they import on their own territories (while giving up exports). 62 out of these countries would not be able to do so due to land constraints (Table 5.1), which renders them dependent on virtual land imports. That means, only a few countries, especially the US, Kanada, Russia, Australia and Argentina, could achieve self-sufficiency (regarding the crop products considered here) without having to expand cropland and use more water. As shown in Fig. 5.1a, especially Africa, Europe and the Middle East would not be able to meet the needs due to limited resource availability. While some countries in North Africa and the Arabic peninsula appear to face both land and water limitations, some Latin-American and South African countries face only a land limitation. We note that the datasets for managed grasslands (based on Ramankutty et al, 2008, see Fader et al., 2010) and the least productive grasslands (based on Erb et al, 2007, see Krause et al., submitted) – both excluded from AL – could overlap in some regions, since the latter does not differentiate between managed and natural grasslands. Such overlap probably led to the low land availabilities in parts of Africa, the US and Central Asia. (Excluding one of these categories in sensitivity analyses led to a clear overestimation of land availabilities and to unrealistic dependence for the present, especially in Africa, such that the results shown here represent the best approximation given the land use datasets used).

In CUR the required cropland expansion and water consumption increase would be considerable in absolute terms (land: average ~0.87 Mha with highest values >7 Mha for

Table 5.1: Number of countries (out of a total of 197) in need of cropland expansion and water consumption increase for achieving self-sufficiency (for the 11 crops considered), and number of countries that cannot cover these needs with domestic land resources (“unable”). Global numbers of countries not able to cope with the required water consumption were not calculated, since consequences on water availabilities of downstream countries of changes in productivities and land use change were not quantified explicitly.

Productivity and population scenario	Land		Water
	Expansion	Unable	Increase
CUR, 2000	139	62	145
HIG, 2000	54	21	54
POT, 2000	44	14	44
CUR, 2090	143	88	146
HIG, 2090	121	65	124
POT, 2090	101	46	105

Scenario | **Required cropland expansion CE** | **Required water consumption increase WCI**

a) Current productivity, population of 2000

b) Potential productivity, population of 2000

c) Potential productivity, population of 2090

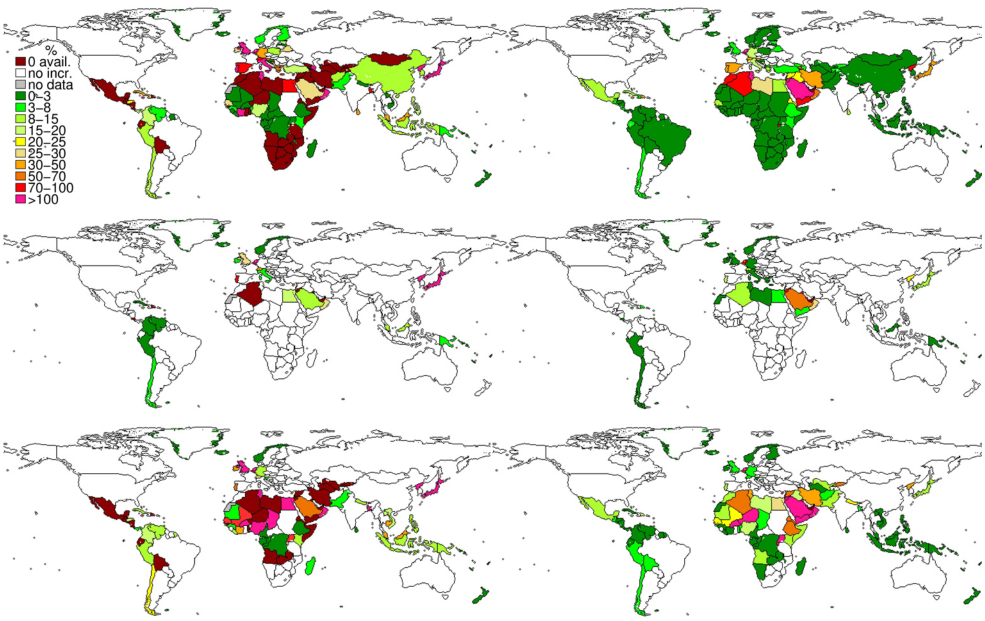

Figure 5.1: Required cropland expansion (CE) and water consumption increase (WCI) in the current situation and for different population numbers and potential productivity (POT). Numbers in percent of available productive land (left) and available renewable water resources (right). Dark red and pink colours indicate inability to cope with the needs with own resources.

The Netherlands, North Korea, Mexico and Japan; water: average ~3.4 km^3 with highest values of 72 km^3 and 49 km^3 for Japan and Mexico, respectively; data not shown, but see Fig. 6c and 7c in Fader et al., 2011). In fact, crop area and water consumption would have to be more than doubled in about 40 countries.

Under productivity increases significantly fewer countries would need cropland expansion and water consumption increase to reach self-sufficiency (54 and 44; Table 5.1). They are mainly situated in the Andean and Mediterranean regions (Fig. 5.1b, Fig. 5.D1a). Although absolute values in POT and HIG are often relatively small (land: average ~0.38-0.54 Mha; water: average ~1.5-2 km^3; data not shown), they still would mean a challenge for many countries in relation to the current levels of water consumption and cropland extent (more than a doubling of cropland in e.g. Saudi Arabia and Portugal, and more than a doubling of crop water consumption in e.g. Chile and The Netherlands; data not shown).

Thus, productivity increases can significantly reduce the number of countries unable to achieve the self-sufficiency levels envisaged here with their own land resources, but even in POT, no less than 14 – mostly small – countries would still be dependent on external land resources (Table 5.1). Moreover, especially countries in the Middle East would not be able to cope with the required water consumption increases: Kuwait, Israel and Qatar are unable to produce what they currently consume even in the POT scenario.

5.3.2 Cropland expansion and water consumption increases for population in 2090

Population change would result in more countries needing cropland expansion and water consumption increases in all productivity scenarios (Table 5.1). The required cropland expansion and water consumption increase would reach on average ~6 Mha and ~24 km^3, respectively, under current productivities, which would be more than a tripling of cropland and water consumption in about 70 countries. Without productivity increases, almost the whole of Africa and the Middle East would become dependent on imports or show increases in dependence (Fig. 5.2a), and ~50% of all countries would not be able to provide on their territory, and under the constraints assumed in our scenarios, the land required for producing the crop products under conditions of SRES A2r population projections for 2090 (Fig. 5.D1b). Some countries that do not have this limitation today, such as Argentina, the US, Sudan, India or Indonesia, would need extra domestic land resources that are not available (Fig. 5.D1b).

Productivity increases would lead to a small reduction of the number of countries requiring cropland expansion and water consumption increase to reach the required production level (Table 5.1, Fig. 5.1c, Fig. 5.D1c). Still, Colombia and Malaysia, for example, would need to more than double current crop area and water consumption to produce what they consume even in the POT scenario (data not shown).

Population change along with achievement of higher or potential productivities would relax dependence on virtual land imports in some South African countries but dependence on virtual land and water for many African and Middle East countries would nonetheless be stronger than today (Fig. 5.2b,c).

In summary, the effects of population growth are projected to overwhelm productivity increases in many regions, such that many countries in North Africa and the Middle East will become (more) dependent on virtual land and water imports by 2090 than today even if higher crop productivities were to be in place.

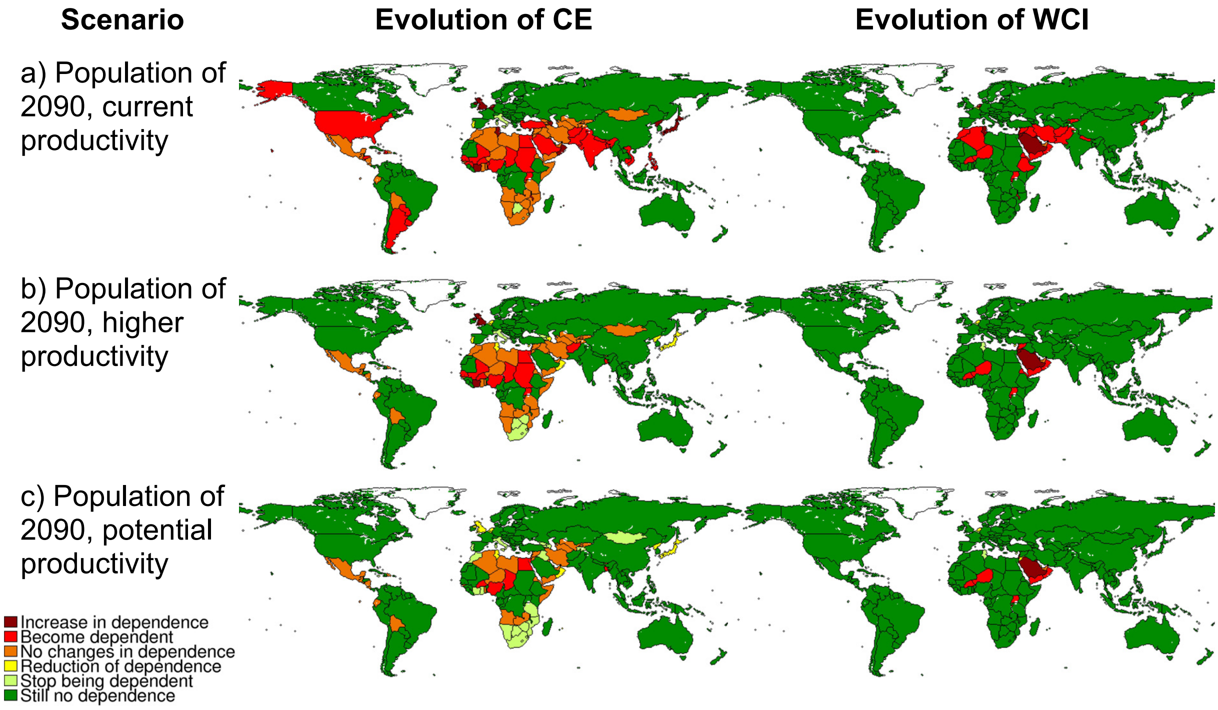

Figure 5.2: Evolution of cropland expansion (CE) and water consumption increase (WCI) under different productivity scenarios from 2000 to 2090. **Increase in dependence** = CE/WCI 2000 > 100%, CE/WCI 2090 >100%, CE/WCI 2090 > CE/WCI 2000. **Become dependent** = CE/WCI 2000 <100%, CE/WCI 2090 >100%. **No changes in dependence** = CE/WCI 2000 > 100%, CE/WCI 2090 >100%, CE/WCI 2090 = CE/WCI 2000. **Reduction of dependence** = CE/WCI 2000 > 100%, CE/WCI 2090 >100%, CE/WCI 2090 < CE/WCI 2000. **Stop being dependent** = CE/WCI 2000 > 100%, CE/WCI 2090 <100%. **Still no dependence** = CE/WCI 2000 < 100%, CE/WCI 2090 <100%.

5.3.3 Number of people affected

Currently, in almost every country less than 20 million people depend on external water and land resources, China and Japan being the countries with the highest numbers in absolute terms (data not shown). Especially North African, Arabic and Andean countries have, however, the highest shares (>50%) of population depending on external land and water resources (Fig. 5.3a). Globally, 15% of the current population (900 million people) depend on land and water resources not situated in their home countries.

Even assuming that the potential for cropland expansion would be fully exploited in each country would leave 5% of the current world population depending on *ex situ* land resources (300 million people), many of these living in Japan, Algeria, Iran and Mexico (data not shown).

With population increase in many regions other than Europe, a country could decide to extend cropland and increase water consumption to cope with the higher food demand, increase agricultural imports, increase agricultural productivities or a mixture of these three options (see Fig. 5.4a for the global number of people affected in each pathway).

Population change will add 6500 million people (7400 minus 900, Fig. 5.4a) that could not be fed domestically by 2090 (60% of world population) if current cropland and water consumption stayed constant and productivity increases were not achieved. Especially Asia, Latin America and Africa would be affected in this case (Fig. 5.3b).

Expanding cropland to its maximum availability in each country while maintaining current productivities would

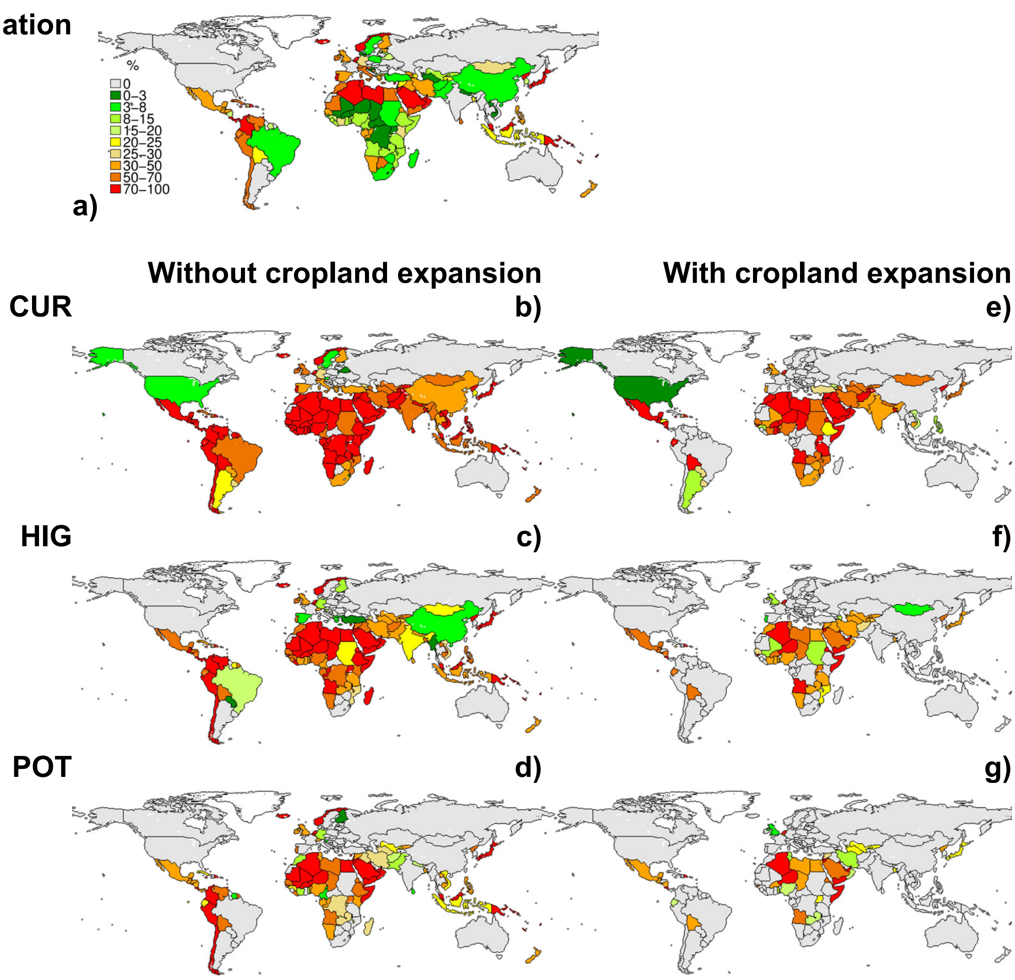

Figure 5.3: Percent of country population dependent on *ex situ* land and water resources, presently (current cropland extent, productivities and population, **a.**) and for the population of 2009, in the different productivity scenarios without (**b.–d.**) and with cropland expansion (**e.–f.**), respectively.

result in 3900 million people (32% of world population) whose diet would depend on land resources not situated in their countries (Fig. 5.4a). Especially North Africa and the Middle East would still be increasing the proportion of their population depending on external resources despite fully expanding cropland to the available area (Fig. 5.3e). This means that cropland expansion alone cannot compensate for population growth in these countries.

Another possibility is increasing agricultural productivities. Achieving higher and potential productivities in all countries without expanding cropland would lead to 4300-2400 million people (35%-20% of world population) still dependent on land resources not situated in their countries (Fig. 5.4a). Absolute numbers are especially high in Asia (data not shown); in terms of percentage of population, the African countries are most affected (Fig. 5.3c,d). This means that increasing productivity alone is neither enough to compensate population growth.

A mixture of expanding cropland to its maximum availability in each country and increasing agricultural productivity would leave 1800 million people (15% of world population) dependent on virtual land imports by 2090, mainly in Africa and the Arabic peninsula (Fig. 5.3f), maintaining globally the current proportion of people

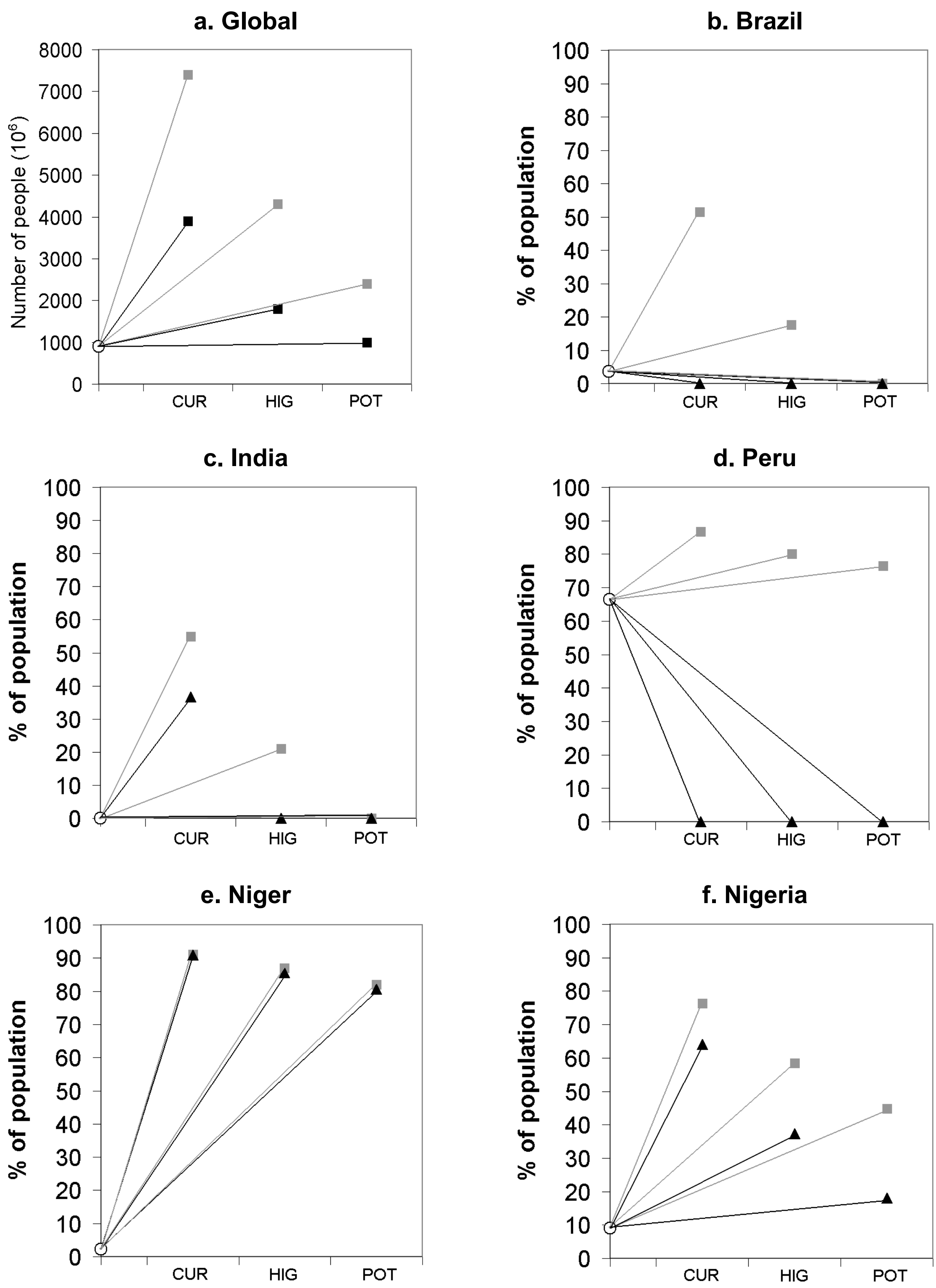

Figure 5.4: Number of people globally dependent on *ex situ* land resources (a.), and percentage of population dependent on *ex situ* land and water resources in different productivity scenarios for selected countries. Lines link the current dependence situation with the dependence in different productivity scenarios. **Open circle** = people or percentage of people dependent assuming population for 2000 and present productivity. **Grey** = people or percentage of people dependent given 2090 population, without cropland expansion. **Black** = people or percentage of people dependent given 2090 population, with cropland expansion.

dependent on external resources, and even allowing for a reduction of dependence in many countries.

Whether expanding cropland or increasing productivity is most effective for reducing the global number of people depending on external resources depends on the degree of productivity increase. It is more effective to expand cropland under current productivities than to reach higher productivities (HIG) without expanding cropland (3900 million dependent people < 4300 million dependent people, see Fig. 5.4a). Achieving potential productivity is, however, more effective than expanding cropland (2400 million people dependent < 3900 million people dependent, see Fig. 5.4a). The optimal mix is different for each country. China, for example, would maintain the proportion of its dependent population by reaching higher productivities without having to expand cropland. Alternatively, China could reduce the level of dependence by expanding cropland without having to improve agricultural productivities (Fig. 5.3). Brazil could even reduce the proportion of its population dependent on external resources by expanding cropland without having to increase agricultural productivities; achieving higher productivities while not expanding is not enough in this case (Fig. 5.4b). India would have to achieve potential productivities or combine higher productivities with cropland expansion, if the proportion of population dependent on external resources should not increase (Fig. 5.4c). Andean countries will have to expand cropland, since even under POT they would have an increased proportion of population depending on external resources (see for example Peru in Fig. 5.4d). Many countries such as Niger, Nigeria, Angola, Yemen and Uzbekistan would have increased proportion of population dependent on external resources, even if they expanded cropland and strongly increased productivity (Fig. 5.4e,f).

5.4 Discussion

5.4.1 General findings

In this study, we analyzed water and land constraints for countries' food self-sufficiency (constrained to major crops), for the current situation, and for three agricultural productivity scenarios, while also considering future population change, as well as potentials for cropland expansion and water consumption increase.

Our findings suggest that a number of countries in North Africa and the Middle East are already dependent on external resources and many will become (more) dependent in the future due to population growth, even if increases in agricultural productivity are achieved.

62 countries, mainly situated in Africa, were found to be unable to produce the crops they currently import/consume, even if their potentials for cropland expansion are taken advantage of. Additionally considering increases in crop productivity leaves 14-21 countries (corresponding to 300-400 million people) unable to provide the land use expansion required; these countries are thus dependent on virtual land imports.

Future population growth will exacerbate this situation. Many countries in Africa, the Middle East and the Andean region will have to strongly expand cropland and water consumption, as well as to improve agricultural productivities, if they do not want the proportion of their population that depends on external land and water resources to increase to levels higher than 50% (or to leave one in two people suffering from mal- or undernourishment).

5.4.2 Comparison with other estimates

Our results are compatible with particular findings from previous studies that used other methods. For example, a high dependence (defined as the ratio of external water footprint to total water footprint

>50%) was shown for Italy, Germany, Japan, the UK, Jordan and The Netherlands (Hoekstra, 2009b). That author's definition is different from ours and does not consider water availabilities, nonetheless there are some similarities in the findings: both studies classify Jordan and The Netherlands as being dependent on country-external water (and land) resources. However, in our study the dependence of the UK, Japan, Italy and Germany is only high (CE > 50%) in case of land resources (Fig. 5.1a).

The Gulf States were presented as being very dependent on agricultural imports (ratio of imports to consumption >89% for wheat, maize, rice and pulses) and connected to this, as vulnerable to external price shocks (Kotilaine, 2010). Our results, even if calculated with a different approach, affirm this picture, showing high water and/or land dependence for all Gulf States, even when accounting for productivity increases (Fig. 5.1a,b, Fig. 5.D1a).

The so-called "national ecological deficit" is defined as the difference of ecological footprint (the area of productive land and aquatic ecosystems required to produce the resources used and to assimilate the wastes produced) and ecologically productive land divided by population (Rees, 1996). This is similar to our estimates for CE in percent of available productive land. The highest national ecological deficits were calculated for The Netherlands (1900%), Belgium (1400%), Korea (950%), Germany (780%), Japan (730%), Switzerland (580%), Denmark (380%), France (280%) and Austria (250%) (Rees, 1996). Our calculations for those countries reveal that as well. The Netherlands (1120%), Belgium (317%), Japan (301%) and North Korea (527%) do not have enough land resources to produce what they currently consume. The difference for the rest of the countries, and the reason for our lower estimates, is probably the fact that his results consider all commodities and also the area required for waste assimilation.

In regards to national studies, high dependence was shown for the UK, with a food self-sufficiency index of 58% (defined as the value of domestic production as share of national consumption) (Cooper, 2007). Our study shows a high dependence on virtual land imports, while the water dependence is relatively low (Fig.5.1a). The self-sufficiency ratio (calories produced domestically divided by calories imported) of Japan was shown to be 41%, the lowest value among developed countries (Honma et al., 2000). Indeed our study showed a very high dependence on virtual land imports, but a relatively low dependence for water (Fig. 5.1a). India's traditional policy of self-sufficiency leads to relatively low current dependence on external resources (see e.g. Chand, 2006), in good agreement with our results. Nevertheless, as reflected by the evaluation of the National River Linking Project which aims to link 37 rivers in India to assure food production for the rapidly growing population (Verma et al., 2009), its dependence on imports could grow considerably, and would only be low if productivity increases were achieved (Fig. 5.4c). Concerning Tunisia, we calculated land and water requirements for self-sufficiency under current productivities to be higher than the available resources. This means that Tunisia is already dependent on virtual water and land imports (Fig. 5.1a). This situation will worsen under population change if improvements of agricultural productivities were not to materialize (Fig. 5.2). This is in good agreement with the study by Besbes et al. (2010) that projects increasing dependence of Tunisia in absence of strong productivity increases, calculating water dependency indexes (virtual imports/total use) of 31% (currently) and 42% (population change).

Our study projects 4.3 billion people to be dependent on external resources by 2090 under the SRES A2r population scenario, with these living mainly in Africa and the Middle East, and when taking into account population growth as well as higher future productivities (Fig. 5.4a and 5.3c). This is similar to other estimates for the future (note the different target years): a) 3.8-4.2 billion people living in countries in need of cropland expansion by 2050 (Falkenmark et al., 2009). b) 3.93 billion people living in countries not able to be self-sufficient by 2050 (Rockström et al., 2009), c) 4.6 billion people dependent on imports by 2025 (Falkenmark, 1997). Note, however, that these studies worked with standard diets rather than actual consumption and estimated water productivity increases and in some cases water requirements as global estimates without accounting for country-specific conditions.

5.4.3 Implications of study results

The implications of the study results are diverse and certainly dependent on a number of local and/or regional factors. For example, many African and Asian developing countries are shown here to become (more) dependent in future. Many of these countries are already today facing poverty, lack of infrastructure and low purchasing power and could also be limited in the future in their ability to take part in virtual water trade (Yang and Zehnder, 2007). They could still opt for improving agricultural productivity, and in some cases, for expanding cropland and increasing blue water use in order to meet the crop demand of their likely future population. It remains to be quantified more specifically for each country how such an objective could be achieved, but extensive, agro-ecological techniques and expansion of agro-forestry are being discussed as promising and relatively cheap pathways (Altieri, 2002; Pretty et al., 2003; Rost et al., 2009). Other countries with stronger economies could choose a mixed path: increasing import dependence for certain agricultural products while promoting higher agricultural productivities of other crops. The latter could be achieved by a variety of measures including input subsidies, investment in agricultural field experiments, technical support for farmers, improving the quality and reliability of irrigation water, improving rural infrastructure, facilitating access to credits, or developing water right systems (e.g. Diagne and Zeller, 2001; Yu and Fan, 2001; Comprehensive Assessment of Water Management in Agriculture, 2007; Denning et al., 2009; Butler and Cornaggia, 2011). Other nations with abundant financial means, population growth and unfavourable natural conditions (e.g. the Arabic peninsula) will probably maintain their present international trade relations in order to imports virtual resources. In doing so, they could specialize in other sectors (e.g. high value crops, tourism), as is already the case, in order to create mutual dependence and thus reduce risk (Morrison and Sarris, 2007; Burger et al., 2010). Increasing stocks of crops would be recommendable irrespectively of the pathway chosen, in order to avoid negative consequences of international supply disruptions and natural disasters (von Davier et al., 2010). As an alternative to adapting to or managing increases in dependence, a country could approach the causes of these increases through manipulation of diets or control of demographic development, to name just two examples.

5.4.4 Shortcomings of this study and perspectives for future research

Even if the results are largely plausible and in good agreement with other studies in terms of the magnitude and patterns of dependence (see also Fader et al., 2011, for an evaluation of the underlying virtual water and land flows quantities), the present work necessarily has some limitations, related primarily to the scenario definitions (see further below) and to uncertainties in the data used. For example, our definition of ARWR is quite restrictive, since we excluded fossil groundwater, environmental flow requirements, industrial and domestic water use, water as diverted from other regions, and seawater desalination. Inclusion of either of these optional (yet mostly unsustainable) water uses, or combinations thereof, could be addressed in dedicated tradeoffs studies. Some detailed analyses of the sensitivity of results are provided in the appendix, using different data on water availability ARWR (**Appendix 5.A**), considering areas protected and areas worthy of protection as available for agricultural expansion (**Appendix 5.B**), including exports in the expected production (**Appendix 5.E**), omitting environmental flows requirements (**Appendix 5.F**), and optimising crop water productivity instead of crop yields (**Appendix 5.G**). From these analyses it can be inferred that only a few countries show notable differences in the key results presented here if the sustainability criteria are relaxed (using protected areas, areas worthy of protection and water reserved for environmental flows for agriculture), if other water availability data are used, or if water productivity rather than yield is optimised. Thus, the results shown in the former sections are mainly robust.

In the scenarios of cropland expansion, we used country averages of crop yields and water productivities (averaged over irrigated and rainfed types, see Methods) for the newly cultivated areas, and multiple cropping systems and a potential introduction of new varieties were not considered. Further studies will have to account in more detail for such processes and, more importantly, for spatially explicit scenarios of changes in water availability and land use, including scenarios of land use for bioenergy production (Beringer et al., 2011). This, in union with more refined (more realistic) representations of prospective productivity increases or, respectively, technological change requirements, could be accomplished by coupling the LPJmL model with an agro-economic land use allocation model (see Lotze-Campen et al., 2009, for earlier applications of this type). Also, the results presented solely rely on the assumed population development (A2r), which is a high population scenario. Additional analyses (data not shown) indicate that considering lower population scenarios such as those from the SRES B1 or B2 scenarios will yield lower dependence. Nevertheless, we decided to show and analyse the results for A2r in order to offer the upper limit of dependence.

We furthermore note that investigation of climate change and CO_2 fertilisation effects on water use, crop growth and growing seasons was beyond the scope of this study. These processes will affect future water and land availabilities, even if their effects are frequently smaller than those of population change (Vörösmarty et al., 2000; Rockström et al., 2009; Gerten et al., 2011). Forthcoming studies will have to address these issues using large ensembles of climate models, and model runs with and without consideration of direct CO_2 effects on plants (while at the same time considering nutrient limitations that may constrain the CO_2 effect).

We emphasise that this study considered productivity increases and land/water requirements of 11 major crops only. Even if the growing areas and blue water consumption of all other agricultural commodities were taken into account, which were kept constant in HIG and POT, the production increase needed for those commodities was not considered. LPJmL is being developed further to simulate more crop types and also the livestock sector (see Gerten et al., 2011, for first steps in this direction). This will also allow for analyses of potential future diet changes per country, such as shifts towards more milk and meat consumption with rising income (Delgado, 2003; Steinfeld et al., 2006; Smil, 2002), inequality in diets within a country, or achievement of specific target diets (see Introduction), which were neglected in the present scenario analysis. This study was not designed to provide projections of food security by the end of this century nor to provide an analysis of the carrying capacity of the Earth. Its purpose was rather to quantify the extent to which the still available water and land resources constrain countries' capacity to grow on their own territory the crops consumed by their inhabitants. As such, it paves the way for more elaborate analyses and, particularly, sheds light on the importance of international trade to global food security. On the one hand, international trade may assist in increasing the sustainability of the world by managing resources across borders jointly. On the other hand, dependence of nations on resources outside of their territories – not by choice, but by necessity – indicates the extent to which globalization effects have already led to lock-ins into particular types of international structures, the maintenance and security of which is then a matter of substantial importance.

Appendix

5.A) Results when using other water availability data

The present study uses data on water availability from LPJmL ($ARWR_{LPJmL}$). We here tested how results would be affected if other data sources would be used, namely:

- AQUASTAT actual renewable water resources, defined as the sum of the average flow of rivers and recharge of aquifers generated from endogenous precipitation, and the inflows from upstream countries, minus the outflow reserved for downstream countries through formal or informal agreement or treaties (FAO, 2003).
- The Pacific Institute (PI) current renewable water resources, defined as the renewable surface water and groundwater supply, including surface inflows from neighboring countries (Gleick, 2000). This is a compilation from many sources, including in some cases AQUASTAT values.

Municipal and industrial water use was subtracted and 30% was reserved for environmental flows, as explained in section 5.2.3, obtaining $ARWR_{FAO}$ and $ARWR_{PI}$.

Figure 5.A1 gives an overview of the global availability of water resources and its spatial patterns: the PI data present the highest global water resources, followed very closely by the AQUASTAT and then LPJmL. As can be observed, there are many similarities in the spatial patterns and some differences for e.g. India, Saudi Arabia, some African countries like Libya and some Andean countries.

Figure 5.A2 shows the number of countries in each WCI class when using $ARWR_{LPJmL}$. Black error bars indicate the maximal and minimal variation in these numbers when considering $ARWR_{PI}$ and $ARWR_{FAO}$. Please focus on the variation of the number of countries due to different water availability data since, as stated in Table 5.1, the absolute numbers can be inaccurate due to neglecting the influence of cropland expansion in the water availability of downstream countries. As can be observed, using water availabilities from other sources would lead in the current situation to negligible variations (see black error bars, Fig. 5.A2, left panel) and also to more countries without data, which emphasizes the usefulness of models for global water availability studies. In the case considering population change the variation is again small, mainly with more countries with WCI between 50-100% and less countries in the class >100% (see black error bars, Fig. 5.A2, right panel). From the latter group, eight countries that in our analysis are shown to be unable to cover the needed WCI would be able to cover them when considering other availability data: Afghanistan, Belgium, The Netherlands, Iraq, Iran, Kyrgyzstan, Nepal and North Korea. Caution is thus recommended when considering the results concerning water constraints for these countries.

Nevertheless, the water constraints shown for almost every country, especially the ones with critical situations in North Africa and the Arabic peninsula are robust, i.e. existent irrespective of the water availability data used.

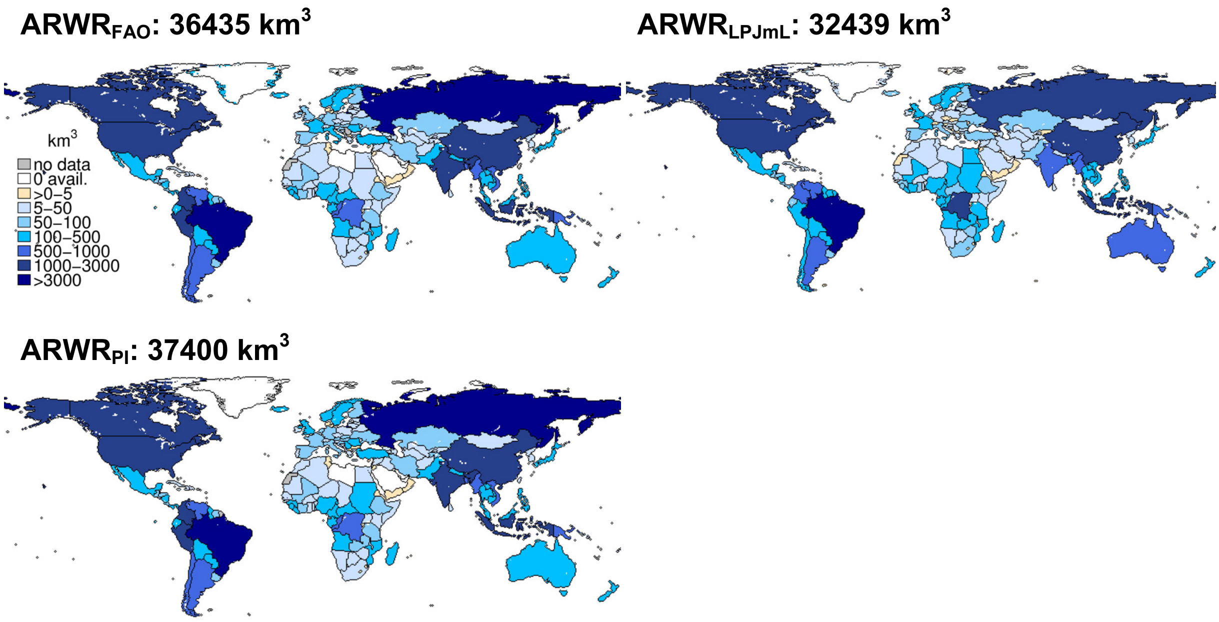

Figure 5.A1: Available renewable water resources per country and global availability numbers. $ARWR_{LPJmL}$ are the estimates used for the results presented in section 5.3.

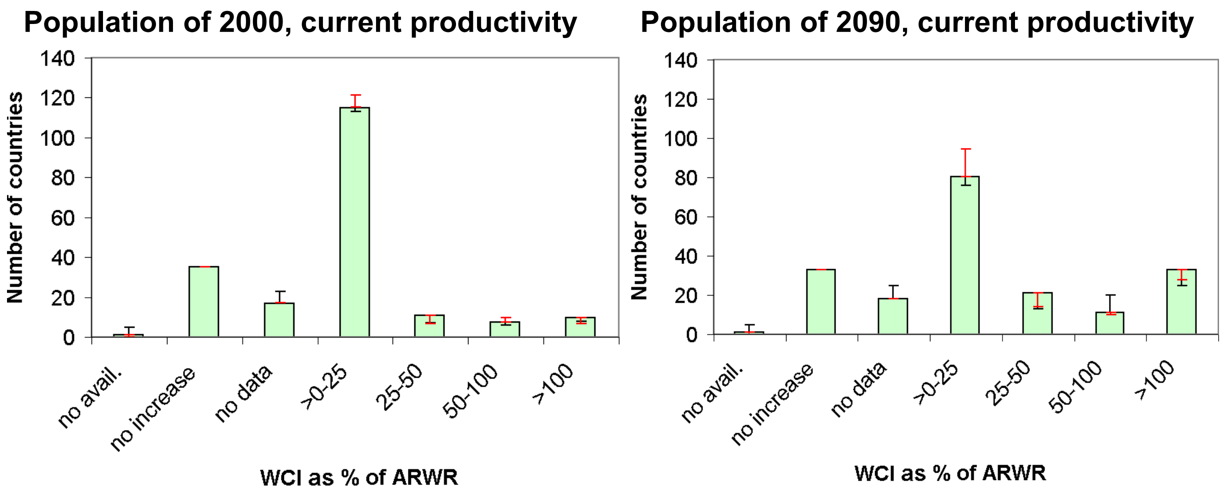

Figure 5.A2: Number of countries in the water-consumption-increase-classes for current population (left) and population of 2090 (right), in both cases under current agricultural productivities (CUR). Black error bars indicate the variation when considering data on water availability other than calculated by LPJmL, red error bars indicate the variation when omitting environmental flow requirements.

5.B) Results when protected areas and areas worthy of protection were made available for agricultural expansion

One could ask if the ability of a country to reach the expected production in each scenario would be different if we would consider protected areas and areas worthy of protection as available for agriculture. In order to test this, we defined following scenarios:

$$AL_{Unused} = L - Ur - Un - LG - TC - MG - F \quad \text{(B1)}$$

$$AL_{Protected} = AL_{Unused} - PA \quad \text{(B2)}$$

$$AL_{Sustaianable} = AL_{Protected} - WP \qquad (B3)$$

where L is the total country area, Ur is urban land, Un is unproductive, unused land (production <20 gC m^{-2}), LG is least productive grazing land (production between 20 and 200 gC m^{-2}, all from Erb et al., 2007), TC is total cropland, MG are managed grasslands areas (both as in Fader et al., 2010), F is the areas used for forestry production (adapted from Erb et al., 2007), PA are protected areas (IUCN classes I and II, see UNEP-WCMC, 2007) and WP are areas worthy of protection (the union of Green Peace's Intact forest landscapes and WRI's frontier forest, see Greenpeace International, 2005, Bryant et al., 1997). See more details in Krause et al. (submitted) and references therein. $AL_{Sustainable}$ is the scenario used in this study, see section 5.2.4.

Figure 5.B1 gives an overview of the global availability of land resources, spatial patterns and areas included, respectively. The most restrictive land scenario is $AL_{Sustainable}$, being ~45% of the AL_{Unused} scenario. Especially the US, tropical South America, Congo, Russia, Indonesia and India present significantly more available land if protected areas and areas worthy of protection were regarded as available for agricultural expansion. This, however, has little effect for the countries not able to feed their population by 2090 assuming higher productivities (data not shown). Exceptions are only Ecuador and Bolivia, becoming able to reach the expected production if these areas are available for agricultural expansion. These countries could be thus able to reach the expected production, but only at the cost of natural ecosystems. In general, using the current protected areas and areas worthy of protection for agricultural purposes would not be enough to provide domestically the crops the population will need by 2090, even assuming higher agricultural productivities.

The global number of people depending on virtual land imports shows some variation when using $AL_{Protected}$ and AL_{Unused}. 100-200 million people, especially in Japan, Saudi Arabia, Bolivia and Ecuador (data not shown) could escape the dependence on external land resources if each nation would use the protected areas and areas worthy of protection for agricultural expansion in addition to unused land, in order to produce the crop products they consume. These would, however, go in detriment of terrestrial ecosystems, boomeranging in the long run into negative consequences for agricultures.

5.C) Details on the calculation of the number of people dependent on external resources in each scenario

For assessing the number of people whose food is produced with land and water resources situated outside their countries at national and global level, we first calculated the land and water requirements per capita as sum of the requirements to replace imports and the requirements for maintaining the part of the production consumed domestically divided by the total population number. After that, we divided the absolute land expansion and water consumption increase in each scenario by the per capita requirements, obtaining the amount of people affected in each case.

The absolute land expansion is:

- in case of no expansion and for current productivities: NLS (when negative).
- in case of expansion and for current productivities: NLS*(-1)–AL (when NLS negative), i.e. the part of NLS that can not be fulfilled after expansion to the available productive land.
- in case of no expansion and for higher/potential productivities: CE: (see nominator of equation 3).
- in case of expansion, and for higher/potential productivities: CE–AL, i.e the part of CE that can not be fulfilled after expansion to the available productive land.

The absolute water consumption increase is:

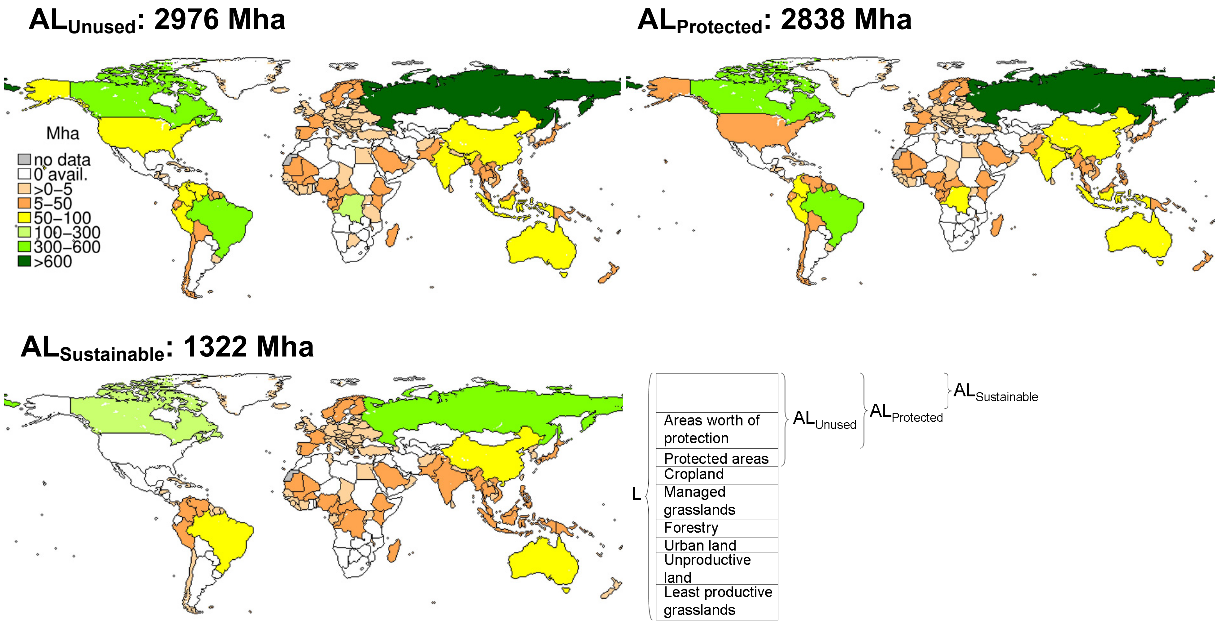

Figure 5.B1: Available productive land per country and global availability numbers. $AL_{Sustainable}$ are the estimates used for the results presented in section 5.3.

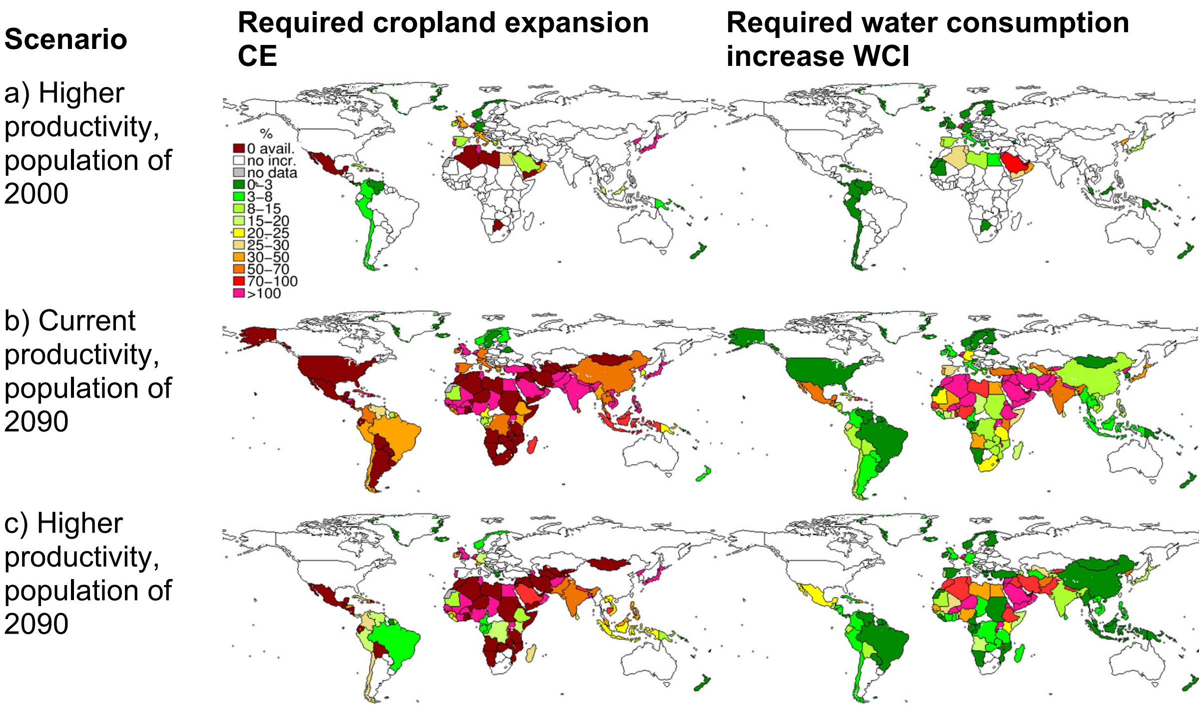

Figure 5.D1: Required cropland expansion (CE) and water consumption increase (WCI) for different population numbers and productivity scenarios. Numbers in percent of available productive land (left) and available renewable water resources (right). Dark red and pink colours indicate inability to cope with the needs with own resources.

- in case of no water consumption increase and for current productivities: NWS (when negative).
- in case of water consumption increase and for current productivities: NWS*(-1)–ARWR (when NWS negative), i.e. the part of NWS that can not be fulfilled after increase of water consumption to the available renewable water resources.
- in case of no water consumption increase and for higher/potential productivities: WCI: (see nominator of equation 4).
- in case of water consumption increase, and for higher/potential productivities: WCI–ARWR, i.e the part of WCI that can not be fulfilled after increase of water consumption to the available renewable water resources.

Per capita land and water requirements are calculated by dividing the land and water that would be needed to produce what is currently consumed by the population of 2000 (assuming no differences in diets within each country). Per capita land requirements are thus:

- in case of current productivities: (current sowing area+NLS)/population.
- in case of higher and potential productivities: (current sowing area+CE)/population (see nominator of equation 3).

Analogously, per capita water requirements are:

- in case of current productivities: (E+NWS)/population.
- in case of higher and potential productivities: (E+WCI)/population (see nominator of equation 4).

5.E) Results when using another expected production

If we consider that the economies of many countries depend on their agricultural export sectors, one could argue that the production needed to assure food security is determined by the current imports plus the current domestic production (without subtracting the current exports). We have to remark that this is a case that can not be consider for all countries at the same time, since if there is no country importing agricultural products, there would not be any country exporting them. But it is a case that can be looked at for each country separately.

In this scenario, the equations (1) and (2) would have to be modified as follows:

$$CE=\frac{LS}{AL}*100 \qquad (E1)$$

$$WCI=\frac{WS}{ARWR}*100 \qquad (E2)$$

where land and water savings (LS, WS) are the amount of land and water that a country saves through imports, or the other way round, the amount of water that it would need for the own production of the imported goods. WS is computed by multiplying the imported amounts of crops by the CFT-specific virtual water content of the importing country (see Eq. 18 in Fader et al., 2011). LS is computed by dividing the imported amounts by the average CFT-yield of the importing country (see Eq. 19 in Fader et al., 2011). If CE and WCI > 100%, the country would not have enough available land and water to replace imports with own production.

Also the results of equations (3) and (4) would differ since $P_{CFT,Exp}$ would have a different value.

Figure 5.E1 shows a selection of the study results under these assumptions. As expected, the dependence increases for a number of countries, including Argentina, India, Brazil, China and the US (compare Fig. 5.E1a and Fig. 5.3a). Adding population change until 2090 especially the US and Brazil (without cropland expansion) would become more dependent from virtual resources import in the future, even considering productivity increases, if land

and water requirements for the production of export goods were taken into account (compare Fig. 5.E1b and Fig. 5.3c). Considering cropland expansion together with higher productivities still show the US and Argentina as more dependent if exports are included in the expected production (compare Fig. 5.E1c and Fig. 5.3f).

5.F) Results when not considering environmental flow requirements

Figure 5.A2 shows the number of countries in each WCI class after $ARWR_{LPJmL}$. Red error bars indicate the variation when environmental flow requirements are not subtracted from the water availabilities and thus considered available for irrigation. It can be observed that both in the current situation (left panel) and considering population change (right panel) the number of countries in the class 0-25% is higher and in the classes 25-50% and >100% lower. From the latter class, Malawi, Dominican Republic, North Korea, Ethiopia and Belgium are not able to cover the increases in water consumption needed for food self-sufficiency without using the water required by aquatic ecosystems for agriculture (assuming constant productivities). For the rest of the countries shown as unable, especially in North Africa and the Middle East, these results are valid even if no water for environmental flow requirements is reserved.

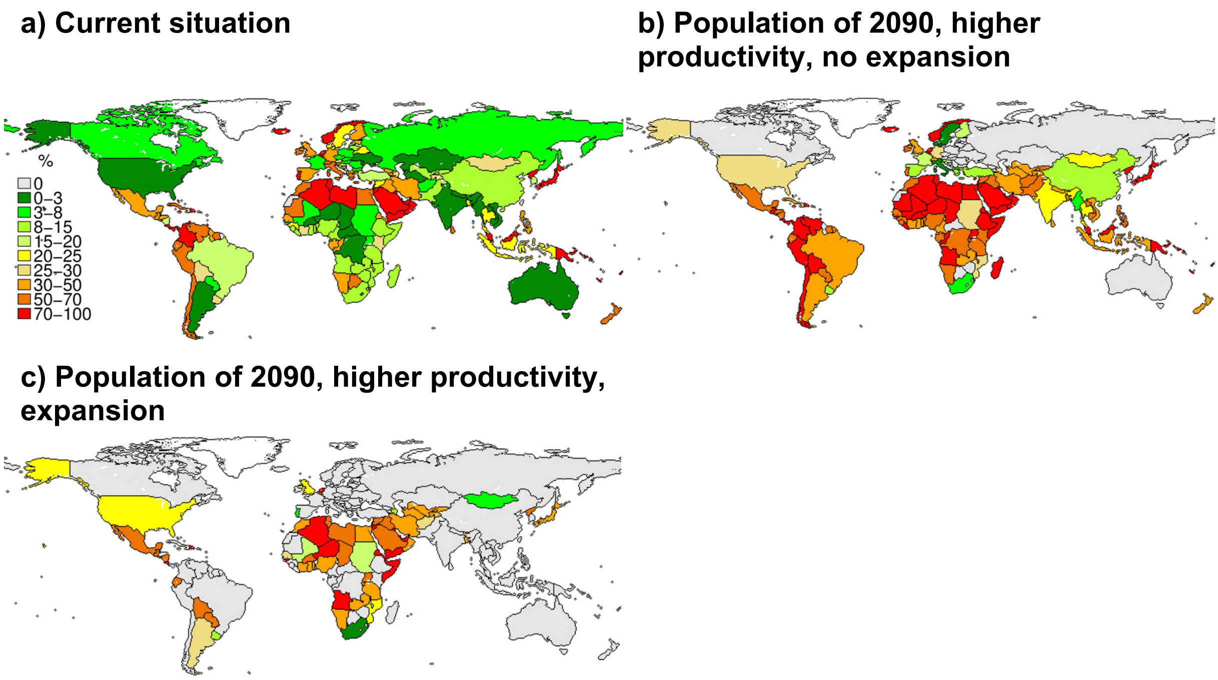

Figure 5.E1: People dependent on land and water resources not situated in their countries as percent of country population when including the current exports in the expected scenario production.

5.G) Results when optimizing water productivity instead of yields

Even if Y and VWC are correlated, the highest yields do not always occur together with the highest water productivity (=the lowest VWC). Therefore we tested how the results would be if instead of choosing the best agricultural management to achieve the highest Y (as explained in section 5.2.2) we would choose the best agricultural management to achieve the lowest VWC. For that, management intensities at country level were systematically varied between 1 and 7. The run with the lowest VWC output (average of rainfed and irrigated) was chosen for each country and each CFT.

Maximizing Y and minimizing VWC lead in some cases to different VWC and Y, but these differences were not big enough to produce different results concerning the ability of a country to reach the expected production in the POT scenario in 2000. All countries shown to be unable when optimizing Y remain so when VWC is optimized. For 2090, only The Netherlands, Libya and Uganda show a difference, being able when optimizing VWC and not being able when optimizing Y.

This confirms that there is for most of the countries a coupling of water and land productivities (the higher Y, the lower the VWC). The results shown in the former sections are thus robust and mainly not dependent on whether the management is aimed to lead to higher Y or lower VWC. More research is however needed, especially in irrigated areas, to explore how to achieve win-win situations (higher, economic useful yields and lower, water-saving VWC).

Acknowledgements

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Chapter 6

Conclusions and outlook

This study makes a step forward in the analysis of current and future land and water productivities, current water consumption and land use, their international virtual flows, and in the assessment of current and future dependence on external land and water resources. It comes to the main conclusion that current production of food is not longer exclusively connected to local resources' availabilities. Instead of that, virtual flows, and especially dependence on *ex situ* land and water resources, are widespread and co-shape the global picture and regional patterns of human appropriation of water and land. More importantly, dependence on *ex situ* water and land resources is expected to increase, or at least, change in a complex way, depending on population growth, climate change and improvements in agricultural productivities.

In the following I will resume the main results of this PhD thesis, discuss on their implications, give recommendations for future work and after that, offer an overview of the innovative aspects included in this work.

Despite the model and input uncertainties discussed in each chapter, and besides the intrinsic uncertainty about future developments, some general conclusions can be drawn:

(1) There are high potentials for improvement in crop water productivity and yields in tropical and subtropical regions, especially in Africa, and in Southeast Asia (Chapter 2 and 3). Economic incentives and affordable technologies for more efficient, sustainable water and land use should thus be offered in order to close the gap between current and potential productivities.

(2) Current spatial patterns of agricultural yields and water productivity result from many interacting factors, including climate, soil and agricultural management. Water stress and length of growing periods seem to be important determining factors for water productivity (Chapter 2). This is why management towards more efficient use of water and land should be planned in an integrated land/water framework and under consideration of local knowledge.

(3) Temperature and precipitation change tend to have negative effects for water and land productivities (by the middle of the century, global average yield decrease up to 13%; virtual water content increases of ~10-20% in many areas), with the exception of the northern high latitudes (Chapter 2 and 3). From a water and land use productivity point of view, climate mitigation and adaptation are thus necessary almost in all countries.

(4) Future development of yields and water productivities will depend mainly on the degree of realization of the positive effects of CO_2 fertilization. In general, yield increases and higher water productivities are expected if full CO_2 fertilization is accounted for (by the middle of the century, global average

yield increases of 8-22% and virtual water content decreases of ~15-30% in many areas) (Chapter 2 and 3). However, this may prove difficult if nutrient, water and pests and diseases control are not managed in a highly efficient way. More modeling and experimental research is extremely needed on this topic. Moreover, assuring the positive effects of CO_2 fertilization (if not avoidable) should be made by the use of non-polluting fertilizers, pest, weed and disease control and non-degrading irrigation schemes, if productivity gains are meant to be sustainable in time.

(5) Green water dominates the production of crop products, both for own consumption and for export (84% of total water consumption is green, 94% of the external water footprint is constituted by its green component). In general, green virtual water flows and water footprints are also higher than blue ones (Chapter 4). Future hydrological studies should thus account for this resource instead of concentrating on blue water only.

(6) Global water and land productivities are higher under current trade patterns than in a hypothetical world of self-sufficient countries (8% and 5% respectively). And current patterns of virtual land and water flows lead to global water and land savings (~263 km^3 and 41 Mha). This means that self-sufficiency of agricultural products would require higher use of water and land (Chapter 4). This is however linked to current productivity levels, if water and land productivities would increase in net importers, global savings through trade could even become global losses. The implication is thus to increase water and land productivities wherever possible, rather than to increase trade.

(7) Spatial patterns of water footprints differ depending on the computed unit (km^3 or m^3 cap^{-1}) and the type of water considered (green, blue, total). Generally external water footprints are much lower than internal ones: the external blue water footprint represents 6% of the total blue water footprint; the external green water footprint represents 16% of the total green water footprint (Chapter 4). It is thus very important to be clear about the type of water meant and the unit used when analyzing current consumption of water resources and communicating results to the public.

(8) Countries with high water footprints affect mainly the water availability in their countries, since they have low ratios of external to internal water footprints (Chapter 4). Nevertheless, the amount does not provide any information on the environmental impacts of the agricultural export sector. Future studies should approach this topic, highlighting indirect pollution and contribution to land/water scarcity (see Mekonnen et al., 2011, for the quantification of the amount of water needed to dilute pollutants).

(9) According to my analysis, 62 countries, mainly situated in Africa, are not able to produce the crops they consume currently due to land and water constraints, even considering potentials for cropland expansion. Thus, currently, ~900 million people depend on *ex situ* land and water resources (Chapter 5). This indicates that globalization, while helping covering the food demand is linked to potentially risky dependence on other countries' natural resources.

(10) Considering increases in crop productivity leaves 14-21 countries (corresponding to 300-400 million people) unable to meet the land requirements for self-sufficiency in the present time; these are thus depending on virtual land imports (Chapter 5). The implications of these findings will depend on local circumstances, including the economic and demographic development and also cultural and political aspects.

(11) 7400 to 1000 million people might depend on *ex situ* water and land resources by 2090, considering SRES A2r population growth and depending on the degree to which improvements in agricultural

productivities are achieved and cropland areas are extended. Some countries will even experience higher dependence on *ex situ* water and land resources in the future, even if they expanded cropland, increased water consumption and improved agricultural productivities (Chapter 5). This implicates, on the one hand, that more people might depend on factors and situations that they can not influence. On the other hand, this may be a serious problem for countries unable to afford virtual imports. Thus, more research is needed to identify those countries. Moreover, local research, as well as political and economic measures, are necessary to close this gap and hence avoid higher numbers of undernourished people.

(12) Population growth will have to be accompanied in Africa, the Middle East and Andean countries by a strong cropland expansion and water consumption increase, as well as improvement of agricultural productivities, if they do not want that the proportion of their population depending on external land and water resources increase to levels higher than 50%, or in case of lack of financial means, having one of two people suffering from mal- or undernourishment (Chapter 5). The implications of these results are again diverse and certainly dependent on many local/regional factors, such as infrastructure, market access, technical support for farmers and treaties on international trade.

Besides the relevance of this thesis, linked to the importance of water and land resources as it was highlighted in Chapter 1, there are many innovative aspects within this work:

(1) The simulations were performed with the process-based agricultural and hydrology model LPJmL, which, in contrast to former studies (Chapagain and Hoekstra, 2008; Yang et al., 2006; Hanasaki et al., 2010) has a dynamic coupling of water fluxes and plant growth, and simulates at high spatial and temporal resolution (0.5°, daily steps).

(2) This is the first study quantifying the consequences of climate change on water productivity of the major crops worldwide. Since climate change could compensate current efforts for higher water productivities, this is a vital issue.

(3) The quantification of the consequences of climate change for agricultural yields and water productivities accounted for climate uncertainty (by the use of many GCMs), uncertainty in CO_2 fertilization effect and in the case of yields, also for uncertainties in development (by the use of many SRES scenarios). This is a complexity and comprehensiveness not seen before in global studies (compare Tan and Shibasaki, 2003; Rosenzweig and Parry, 1994; Parry et al., 2005).

(4) The quantification of current water footprints was made with a spatial resolution and a comprehensiveness missing until now (based on grid-cell water productivities, differentiating internal/external and green/blue components).

(5) This study is the first quantifying globally virtual land flows and savings and linking them to virtual water flows and savings, contributing to the global picture of human appropriation of natural resources (but see regional studies by van Sleen, 2005 and von Witzke and Noleppa, 2010; as well as studies on ecological footprint by Rees, 1996; Ewing et al., 2010).

(6) Dependence on external water and land resources, taking into account changes in agricultural productivity and population growth, and considering current consumption of crop products, was quantified for the first time in this thesis, giving estimations on the future number of people depending on virtual land and water imports.

(7) All analyses were made at the global scale.

I would like to shortly discuss on this last point. Working at global scale has advantages and disadvantages. On the one hand, it is hard to find a correct and adequate model parametrisation and functioning for all biogeographical regions on Earth. Also global data used as model inputs are usually missing or less accurate than regional or local data. Moreover, global models can not be tuned or calibrated to fit reality in one region, since this could lead to inaccurate results in other regions. Spatial resolution, even if very good compared with other global studies, could be much higher, if the work would be performed at local or regional scale. Finally, certain local or regional aspects, like agricultural traditions, especial crop varieties, etc., that certainly have consequences for water and land use could not be taken into account in this work due to lack of data or incompatibility with the model philosophy.

On the other hand, it is necessary to note, that global studies are needed in order to recognize global trends and threats and create an international framework for local solutions. As stated by the World Water Council (2004) *"virtual water is what really makes water a global issue"*. Hence, the quantification of water footprints, virtual resources flows and dependence on external resources could only be performed accounting for global international trade and countries' differences in land and water productivities.

Global studies also allow recognizing potentials for synergies and compensations, e.g. when more than one region face similar problems or when due to different trends, one country can help counteracting harm in other country. For example, since the high latitudes were identified in this thesis as the "winners" of climate change in terms of land and water productivity (Chapter 2 and 3), they could constitute the future world's "food baskets".

Furthermore, global analyses highlight also the necessity of working on agreements for achieving solutions, since global problems such as climate change can not be solved by only one country or a group of countries. Actually, local or national efforts can be even overcompensated by actions or lack of actions in other places. For example, since this PhD thesis showed that the land and water productivity of tropical and subtropical regions will be mainly negatively affected by temperature and precipitation change, the search for mitigation and adaptation strategies could be through joint efforts.

In sum, global assessments recognize explicitly the connection between all regions on Earth and thus, the very socially relevant objectives stated in Chapter 1 could only be successfully tackled with analyses at global scale. Nevertheless, integration of local, regional and global studies is essential for finding a sustainable path for human land and water use.

All in all, this PhD thesis enhanced system-analytic understanding of agricultural water fluxes and land use, and particularly the role of international trade therein, based on most up-to-date and comprehensive dynamic modelling approaches and guided by novel perspectives on the global water system and its components (green, blue, virtual water).

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Publications

Peer reviewed:

Gerten, D., Heinke, J., Hoff, H., Biemans, H., **Fader, M.**, Waha, K.: Global water availability and requirements for future food production. Journal of Hydrometeorology (in press).

Fader, M., Gerten, D., Thammer, M., Heinke, J., Lotze-Campen, H., Lucht, W., Cramer, W. (2011): Internal and external green-blue agricultural water footprints of nations, and related water and land savings through trade. Hydrol. Earth Syst. Sci. Discuss. 8, 483-527.

Fader, M., Rost, S., Müller, C., Bondeau, A., Gerten, D.: Virtual water content of temperate cereals and maize: Present and potential future patterns. Journal of Hydrology 384 (3-4): 218-231.

Müller, C., Bondeau, A., Popp, A., Waha, K., **Fader, M.** (2009): Climate Change Impacts on Agricultural Yields. Background note for the WDR 2010.

Under review:

Fader, M., Gerten, D., Krause, M., Lucht, W., Cramer, W. Dependence of countries on food imports due to limitations in domestically available land and water resources. Submitted to Global Environmental Change.

Dietrich, J.P., Schmitz C., Müller C., **Fader M.**, Lotze-Campen H., Popp A.: Measuring agricultural land-use intensity. Submitted to Ecological Modelling.

Posters:

Fader, M., Gerten, D., Heinke, J., Lotze-Campen, H., Lucht, W., Cramer, W. (2011): Virtual water flows and footprints of agricultural goods. EGU General Assembly 2011, Vienna.

Fader, M. (2010): Virtual water flows and footprints of agricultural goods. GWSP Conference, Bonn.

Fader, M. (2010): Virtual water content of temperate cereals and maize. IMPRS-ESM Evaluation, Hamburg.

Fader, M. (2010): Virtual water content of temperate cereals and maize: Present and potential future patterns. TERRABITES Symposium, Hamburg.

Fader, M., Graßl, H., Bakan, S. (2006): Comparison of HOAPS-Data with ERA40, NCEP and IPCC 20C3M Data. Poster for evaluation of SFB 512.

Other publications:

Fader, M. (2007): Precipitation variability and landscape degradation in Río Negro (Argentina). Diploma thesis at the Georg-August University Göttingen.

Meyer-Arnek, J., Valks, P., **Fader, M.**, Erbertseder, T. (2006): Estimation of NO_2 amounts emitted from the Portuguese wildfires in 2005: A synergistic use of observations by imaging and atmospheric instruments and chemistry-transport models. Proceedings of the Atmospheric Science Conference held 8-12 May, 2006 at ESRIN, Frascati Italy.

Curriculum Vitae

Name: Marianela Fader
Nationality: Argentine/German
Date of birth: Dec. 28th 1980
Place of Birth: Luján de Cuyo, Mendoza (Argentina)

Address:
Sybelstr. 54
10629 Berlin
0176-6202-2927
Email: marianelafader1@yahoo.de

Education

2007-2011 PhD Student at Potsdam Institute for Climate Impact Research and the International Max Planck Research School on Earth System Modelling

2002-2007 Diploma in Geography at the University of Göttingen
Main subjects: Geography, Secondary subjects: Environmental and Resources Economy, Politics, Bioclimatology

Aug 2006-Jan 2007: Master-Thesis: „Precipitation variability and landscape degradation in Río Negro (Argentina)"

2001 2 Semesters of Geography studies at the Universidad Nacional de Cuyo (Argentina)

1994-2000 Primary and secondary education in Mendoza, Argentina

Teaching (selection)

2010/2011 - Seminar "Physical Geography of South America" (Univ. Potsdam)
2010/2011 - Seminar "Global Water Resources" (Univ. Potsdam)
2006 - SPSS Tutorial class (Univ. Göttingen)
2004 - Tutorial class "Geography: An introduction" (Univ. Göttingen)

Scientific work

Since Oct. 2007. **PhD candidate** at Potsdam Institute for Climate Impact Research, Research Domain Climate Impacts & Vulnerabilities.

2007 **Scientific assistant** at Centre for Tropics and Subtropics (University of Göttingen). General coordination of the international network ReCALL (Agriculture, Forestry, Economics).

2006 **Trainee** at Max Planck Institute for Meteorology. Parameter validation of the project "Hamburg Ocean Atmosphere Parameters and Fluxes from Satellite Data".

2006 **Trainee** at the German Aerospace Center. Analysis of NOx-Emissions from SCIAMACHY data (METEOSAT).

2005-2006 **Technical assistant** at the Geographical Institute (University of Göttingen). Database programming for data concerning hydrological changes on the water and nutrient cycle in catchment areas of Indonesia.

2004-2005 **Administrative assistant** at the Examination Office of the Agricultural Faculty (University of Göttingen). Statistics and database maintenance concerning all examinations and classes.

2005 **Scientific assistant** at the Institute for Rural Development (University of Göttingen). Calculation and analysis of statistics concerning household poverty in Uganda.

2005 **Technical assistant** at the Geographical Institute (University of Göttingen). Statistical and plausibility analysis of interview data from Indonesia concerning social organization and processes of ecological stabilization and destabilisation.

2003-2004 **Student assistant** at the Institute of Agricultural Economy (University of Göttingen). Database maintenance and literature analysis concerning methods and conservation biology in Chile and Indonesia.

Courses and presentations (selection)

2011 EGU General Assembly 2011. **Poster**: "Virtual water flows and footprints of agricultural goods"

2010 GWSP Conference, Bonn. **Presentation**: "Virtual water flows and footprints of agricultural goods"

2010 ALTERNET Summer School, Peyresq. **Presentations**: "Virtual water content and flows of agricultural goods" and "Reducing Regional Vulnerability in the Southern Alps Evaluation Trends and Developing Sustainable Adaptation Strategies and Managing Biodiversity"

2010 TERRABITES Symposium, in Hamburg. **Poster:** "Virtual water content of temperate cereals and maize: Present and potential future patterns".

2009 IMPRS-ESM **Course** on radiation and remote sensing in the atmosphere: an overview, in Hamburg.

2008 COSMOS Summer School, in Hamburg. Lectures and exercises about the COSMOS Model. **Presentation:** "Consequences of a dramatic reduction of soil respiration".

2008 IMAGE-PIK Workshop, in Potsdam. **Presentation:** "Crop Modelling: Challenges".

2008 Global Land Use Data Workshop, in Vienna. **Presentation:** "A new land use dataset for LPJml".

2008 IMAGE Workshop in Bilthoven. **Presentation:** "Towards a new land use dataset for LPJml".

2007 Summer Academy of „Studienstiftung des Deutschen Volkes" in Guidel (France). Topic: Globalization. **Presentation:** "Alexander von Humboldt and Microclimatology".

2006 Summer Academy of „Studienstiftung des Deutschen Volkes" in Guidel (France). Topic: Diversity in different disciplines. **Presentation:** "Influencing the landscape diversity".

2008, 2009, 2010 IMPRS-ESM Retreats. **Presentations:** "Crop water productivity and limitations under global climate change", "Virtual water content of temperate cereals, maize and beef"; "Eating someone else's water: Virtual water flows of agricultural products".

Awards

2005 Scholarship of the "Studienstiftung des Deutschen Volkes" for excellent academic performance and social engagement.

2000 Award for the best High School Graduation Diploma.

2000 First Place at the Literature Competition of „María Celia Vitale de Parejo".

1999-2000 Scholarship of Youth for Understanding (one exchange year in Germany) for excellent academic performance.

1999 Second Place in the national selection of participant for the 8th NASA Seminar on Space Sciences.

1998 Nomination for the state press award "Excellent Teenager".

1998 Gold Medal at the National Olympiads on Social Sciences.

1998 Award for excellent performance at simulated negotiations of the United Nations Security Council.

1997 Scholarship for a course about International Politics in Lagunillas, Chile, due to best performance in selection exams.

1992 Award for the best performance at primary school.

MARIANELA FADER

Erklärung

Hiermit erkläre ich, dass die Arbeit an keiner anderen Hochschule eingereicht sowie selbstständig und nur mit den angegebenen Mitteln angefertigt wurde.

Potsdam, 5. Juli 2011

MARIANELA FADER