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.