Modelling impacts of agriculture on freshwater

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1 Introduction

Agriculture is the main human activity affecting water resources, due to the high volumes of irrigation water consumed for crop production. Eighty to ninety percent of human freshwater consumption is occurring in this sector. Additionally, agricultural activities affect the hydrological cycles through land-use changes, soil modifications and lead to pollution of water bodies. On a local level, these impacts and specific improvement options can be assessed by risk assessment and integrated water resource management.

Modelling the impacts of agriculture on freshwater comprehensively is a difficult task. As illustrated by Fig. 1, freshwater can be impacted by water consumption and also by water pollution. These are influenced by direct

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agricultural activities (e.g. irrigation) as well as by indirect activities for the production of agricultural inputs (e.g. fertilizers, agrochemicals). Assessing multiple environmental impacts and multiple contributing processes in the supply chain across the planet is a core strength of life cycle assessment (LCA), which aims to address this complexity in a comprehensive way (for more information about LCA, refer to chapter 1).

In the past, water use and consumption has not been the focus of LCAs due to various reasons. The first missing part was a clear concept for water flows between the technosphere (man-made environment) and the natural environment. Additionally, the understanding of water 'consumption' differed widely: water use (such as on the bill of water suppliers) is not water consumption from a water resource perspective if it is released back to the environment (Fig. 1). Therefore, a large share of industrial water use is not water consumption. Water consumption mainly occurs through evaporation

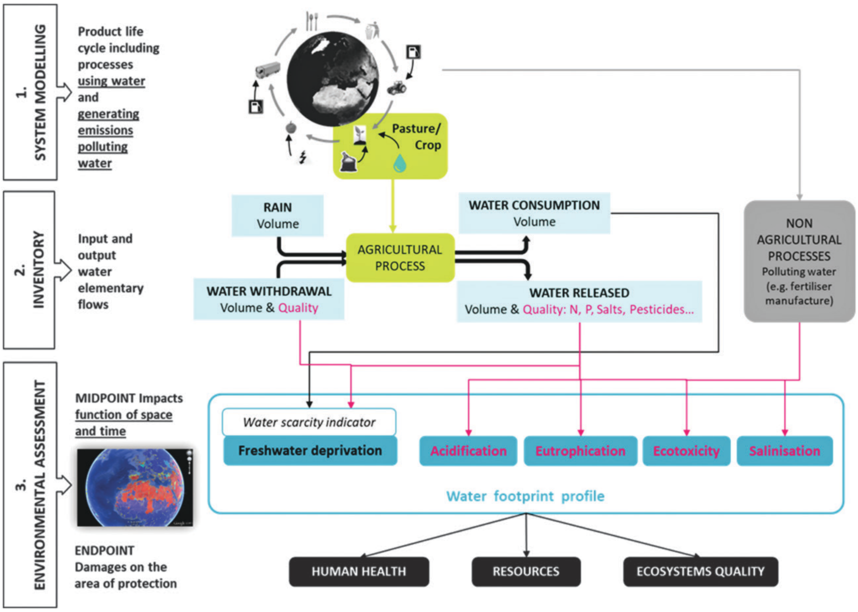

Figure 1 Water-use impact modelling framework in life cycle assessment (LCA): (1) Product life cycle modelling including many processes using and/or polluting water, (2) inventory of water flows for each process in terms of volume and quality (inventory flows requirement depends on the method), (3) environmental impact assessment (function of time and space): water footprint profile includes water deprivation impacts (based on scarcity indicator), but also acidification, eutrophication, ecotoxicity and other impacts related to water degradation. Source: based on Payen (2015).

(in agriculture, from reservoirs and for cooling purposes) and to a lesser extent on freshwater transfer in products to different watersheds. Life cycle databases such as Ecoinvent version 3 and Gabi implemented consistent modelling of water flows to allow for assessment of water consumption effects in LCA (Pfister, 2015). However, water consumption estimates have high uncertainties for several reasons: (1) water is usually cheap and exact measurements of inflow and outflow are not of core interest, (2) it is often a question of water-use efficiency, which can be highly variable and (3) climatic effects on water availability and water losses are difficult to predict. Global databases mainly provide simplified results of water consumption based on global models that do not account for all hydrological parameters. These databases usually differentiate irrigation and industrial water ('blue water') from natural precipitation water supply ('green water'). Additionally, agricultural production is more complex than technical systems, as agriculture is at the interface of natural and technical systems. Irrigation and precipitation (natural flow) are both directly applied to and stored in the soil, which leads to the general issue in agricultural LCA of the technosphere – ecosphere boundary, both in space and in time (further discussed in Pfister, 2015). The duration of the impacts is not limited to the use phase of the soil, but also after, as soil moisture and nutrients might be depleted, soils compacted or eroded. This has been addressed for the livestock sector in a recent FAO activity.

Since water (precipitation and soil moisture) has a large impact on soils, linkages between water consumption and use to other environmental impacts including pollution should be addressed. A framework to address freshwater as a natural resource highlighted the importance for quality aspects beyond quantity (Pradinaud et al., 2019). Pollution of freshwater is treated in other chapters of this book. Of special importance in agriculture are toxic and eutrophying emissions.

Land-use effects on the albedo and thus GHG/energy balance from the timing and type of crop plantations or pastures need to be considered in addition to the effects of land-use change from nature to agriculture on the hydrological cycle and thus water availability. Irrigation also influences albedo and related climate change effects can be considered as impacts related to freshwater use (Munoz et al., 2010).

In the last decade, the UNEP-SETAC working group (WULCA) established a framework to assess water consumption in LCA, which was largely adopted by the ISO 14046 standard on water footprinting and the upcoming guidelines on water footprinting in the livestock sector by the technical advisory group on water of FAO (FAO, 2018a). Internationally agreed terms of importance for this chapter are presented in Box 1.

Box 1 Terms and definitions

Blue water	Freshwater flows originating from run-off or percolation, contributing to freshwater lakes, dams, rivers and aquifers. Soil moisture is blue water if it originates from blue water added through irrigation or owing to hydrological events, such as flooding, from springs or capillary rise.
Green water	Precipitation that is stored as soil moisture and eventually transpired or evaporated from the unsaturated zone.
Precipitation	Liquid or solid products of the condensation of water vapour falling from clouds or deposited from air.
Run-off	Part of the precipitation, which flows towards a water body on the ground surface (surface run-off) or within the soil.
Transpiration	Process by which water from vegetation is transferred into the atmosphere in the form of vapour. Together with evaporation it forms evapotranspiration.
Water availability	Renewable water available in a catchment (blue water).
Water body	Entity of water with definite hydrological, hydrogeomorphological, physical, chemical and biological characteristics in a given geographical area, such as aquifers, lakes, rivers and glaciers.
Water consumption (consumptive water use)	Water consumption is a form of water use (consumptive water use). The term 'water consumption' is used to describe water removed from, but not returned to, the same drainage basin. Water consumption can be because of evaporation, transpiration, integration into a product or release into a different drainage basin or the sea.
Water scarcity footprint (WSF)	Metric that quantifies the potential environmental impacts of water consumption related to water scarcity (based on ISO, 2014).
Water use	Use of water by human activity (ISO, 2014), including consumptive and degradative use (Pfister et al., 2009).
Water withdrawal	Anthropogenic removal of water from any water body or drainage basin, either permanently or temporarily (ISO, 2014).
Water Productivity (WP)	Ratio of the benefit to the amount of green and blue water consumed to produce those benefits in a production process (product units: e.g. mass, energy or nutrition per m^3 water). The WP can be reported with fractions of green and blue water consumed or as total WP.
Water scarcity	Extent to which demand for water compares to the replenishment of water in an area (ISO, 2014).
Water stress	Water scarcity is sometimes referred as water stress and thus used as synonym. However, some authors also include water degradation in water stress.

Source: adapted from FAO (2018a).

2 Modelling impacts of water consumption: water scarcity footprints

Water scarcity impacts or footprints are generally evaluated as a consequence of freshwater consumption (blue water consumption). The ISO 14046 standard on water footprinting (ISO14046, 2014) defines that water scarcity should be addressed spatially and temporally explicitly, in order to reflect environmental relevance of water consumption. Water scarcity is also addressed in the UN Sustainable Development Goals (SDG) 6 'Ensure availability and sustainable management of water and sanitation for all'. The SDG 6.4.2 indicator defines water scarcity as 'freshwater withdrawal as a proportion of available freshwater resources is the ratio between total freshwater withdrawn by major economic sectors and total renewable freshwater resources, after taking into account environmental water requirements'. It therefore refers to withdrawal rather than consumption, which is based on early water scarcity indicators. More recent indicators are based on water consumption instead of withdrawal and it is important to make clear what is accounted for in each indicator. Water withdrawals add pressure to the water resources, especially locally, but neglect water consumption from water storage such as dams for hydropower and irrigation, which have been identified to be a major water consumer, even if often mitigating water scarcity in the driest periods (Scherer and Pfister, 2016). On the other hand, water withdrawal released back to the environment and thus also for further human use is not comparable to water consumption, which is a loss to the freshwater resources in the watershed. For instance, drip irrigation that reduces water withdrawal can lead to increased water consumption (through greater evapotranspiration), and thus increase water scarcity, even if the SDG 6.4.2 indicator is reduced. Therefore, the SDG indicator should not be used standalone to assess water availability and sustainable water management.

2.1 Water consumption and inventory modelling

Various global models assess water consumption of crop production but with a limited level of detail. Some quantify total agricultural water consumption, while others assess crop groups or vegetation classes only (detailed model comparison in Sood and Smakhtin, 2015). These models can be used to calculate total water scarcity of a region, but not for product-level assessments, since different crop characteristics are not accounted for.

Modelling impact on water scarcity at a product or process level requires an inventory of water flows. There is a variety of tools available to do so, ranging from databases to agro-hydrological models (for a detailed review, refer to Payen et al., 2017). The approach adopted should depend on the

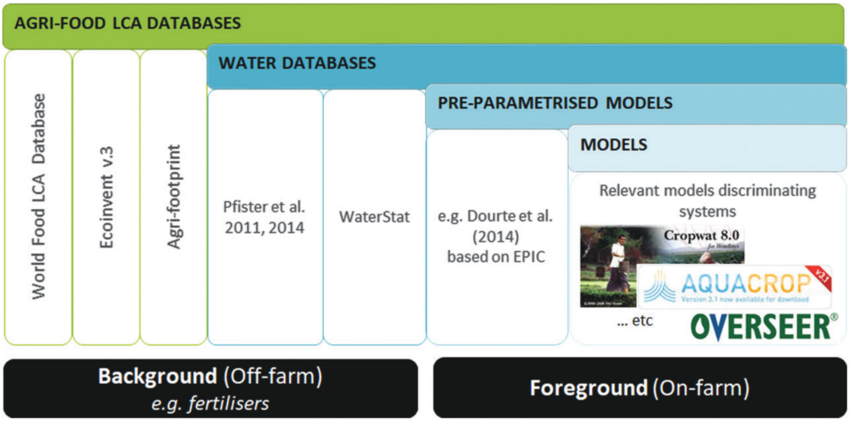

Figure 2 Gradient of possible approaches (models and databases) for the inventory of field water flows and associated type of LCA study.

scope and the objective of the study. Figure 2 illustrates the gradient of possible approaches for the inventory of field water flows and associated type of LCA study.

Water inventory and agri-food LCA databases, such as Ecoinvent (Wernet et al., 2016; Pfister et al., 2016), GABI (Thinkstep, 2019), Agrifootprint (Blonk Agri-footprint, 2014) and World Food LCA database (Nemecek et al., 2015), provide the inventory of water flows for many crops and inputs used on farm (e.g. fertilizer, electricity, agrochemical). Ecoinvent, the largest and most widely used LCI database with transparent system modelling, addressed this issue as a main improvement for their version 3: they integrated a water balance into their entire database (Pfister, 2015). All water inputs and outputs are recorded and the potential mismatch is considered for data improvement efforts. In principle, the water consumption for each process is the sum of water withdrawals and input product water content minus output product water content and water released to freshwater bodies. A process can thus also have negative consumption, for example tap water sourced from a different watershed and used to irrigate a garden: the water is integrated in the product ‘tap water’ and the excess water percolating to groundwater is a release to the environment. Assessing inputs and outputs separately is important in order to allow regionalized assessment as the production might be in different places, such as for the case of the South-North water transfer project in China (Lin et al., 2012).

Detailed water databases provide estimates of water consumed by a crop based on the theoretical crop water consumption (partially with adjustments as in the case of Pfister and Bayer, 2014), but not on the water actually withdrawn and consumed. In addition, databases rely on data and modelling approaches which include limitations regarding the implications of farming practices and the complex mechanisms of field water flows (Payen et al., 2017). Other database, such as Aquastat, are based on statistics but generally lack level of spatial detail (FAO, 2016). Thus, databases are relevant and can be used when the cropping system is at the background level. However, they are too generic to distinguish precise causes of impacts due to the cropping system itself as needed in most agricultural studies where it is at the foreground level, especially where an adaptation of practices is sought (eco-design). In such cases, a detailed modelling approach is required, which is in line with the FAO recommendations on water footprinting (FAO, 2018a).

For the eco-design of cropping systems, the estimation of water flows should be based on a model simulating evapotranspiration, percolation and run-off, which accounts for soil, climate, crop specificities and agricultural management. Note that better estimation of evapotranspiration relies on a separate assessment of evaporation and transpiration. In addition, distinguishing productive water (transpiration related to yield) from non-productive water (evaporation) is valuable information for water management and is in accordance with the ISO standard on water footprinting (ISO 14046, 2014). However, separation of evaporation and transpiration is quite challenging and mainly important for water productivity/efficiency and not for quantifying the impacts (FAO, 2018a).

There is a wide spectrum of models representing the soil-plant-atmosphere ranging from transient state and physically based models to steady-state and bucket models, but there is a gradient in terms of their complexity and data requirements. The agro-hydrological models with a good trade-off between accuracy, simplicity and robustness for LCA eco-design are the FAO functional models: 'CropWat' and 'AquaCrop' (for a description of the models, see Allen et al., 1998; Steduto et al., 2012). Their minimum data requirement makes them suitable for use in LCA. The CropWat model has already been applied in agricultural LCA to estimate crop water requirements; however, it is important to highlight that it may not allow sufficient discrimination of agricultural systems because salinity and nutrient stresses are not accounted for, and run-off and drainage are not differentiated. AquaCrop is an improved version of CropWat and accounts for the effect of salinity, soil fertility and water stress. The main issue with AquaCrop is that it is currently limited to herbaceous crops. However, AquaCrop is supported by a large scientific community which will improve its performance and coverage (both in terms of crop parameters and flexibility for use with GIS and remote sensing data).

Note that this section focussed on the estimate of the volume of water flows, but estimating the quality of the released water flow is also of high relevance for modelling impacts on water quality. This remains a difficult task since it often requires the combined use of databases and modelling. For example, AquaCrop provides an estimate of water salinity, whereas other water quality parameters can be obtained from a nutrient budget.

2.2 Impact assessment and water scarcity footprints

Impact assessment is a key step to identify environmental pressures due to water consumption. Various methods have been developed in the last decade. In general, the methods can be grouped as addressing (1) water scarcity, (2) impacts on human health, (3) impacts on ecosystem quality and (4) impacts on resource depletion. Water scarcity is considered a midpoint indicator, while the others are addressing endpoints (damage oriented). However, it has to be noted that midpoints do not necessarily lead to endpoints, since different mechanisms are addressed for different endpoints.

Water footprinting studies often evaluate midpoint impact on water scarcity, that is providing water scarcity footprint results. Pfister et al. (2009) and Pfister and Bayer (2014) provide the most applied indicator to date, and is based on a water stress index (WSI) representing the water withdrawal-to-availability ratio in an area. The original most-used WSI from 2009 is an annual factor for >11000 watersheds based on WaterGAP2 (Alcamo et al., 2003), while the 2014 indicator is provided on a monthly level to allow for temporally explicit assessments, as required by the ISO standard. Since 2009, various other midpoint indicators have been developed, differing in concepts but generally agreeing that the main function is use-to-availability or consumption-to-availability ratios. In order to overcome the issue that different characterization factors (CFs – refer to Fig. 3 for an illustration) result in different outcomes for comparisons (e.g. Pfister and Lutter, 2016), a consensus method was developed by the UNEP-SETAC working group 'Water Use in LCA (WULCA)' based on the same spatial resolution (using WaterGAP 2) and on monthly levels. Its goal was to provide a generic midpoint for water scarcity, equally relevant for human and ecosystem impacts. It is based on the quantification of the Available WAter Remaining (AWaRe) in an area once the demand for human and ecosystems has been met (Boulay et al., 2017). Thus, it depends not only on the use-to-availability ratio, but also on the absolute water scarcity (i.e. the availability per area). AWaRe represents the potential to deprive another user (human or ecosystem) when consuming water in a given area in relation to the global reference situation of water used. AWaRe was the approach recommended in a Pellston workshop by the United Nation Environmental Program/Society of Environmental Toxicology and Chemistry Life Cycle Initiative (UNEP/ SETAC Life Cycle Initiative) for assessing a water scarcity footprint, in combination with a conceptually different CF for sensitivity assessment (UNEP, 2016). Both indicators rely

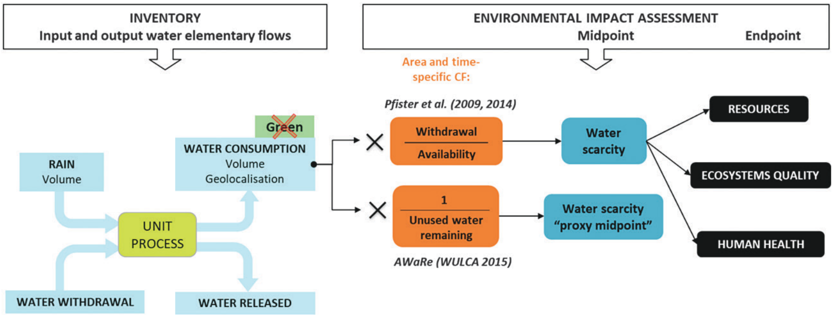

Figure 3 Water footprint impact assessment: from the inventory of water flows to midpoint (water scarcity) and endpoint damages on human health, ecosystem quality and resources. Two widely used midpoint indicators and their corresponding characterization factors (CFs) are represented, namely Pfister et al. (2009), Pfister and Bayer (2014) and AWaRe (Boulay et al., 2017). Note that midpoints do not necessarily lead to endpoints, since different mechanisms are addressed. AWaRe is considered a 'proxy-midpoint' for the endpoints' human health and ecosystem quality. Note that the consumption of green water is not considered as having an impact on water scarcity.

on spatially and temporally explicit CFs used to relate water consumption (inventory) with local pressure on the water resource (Fig. 3). Application of both indicators can be used to test the robustness of the results and compare with previous studies.

LCA methods can also account for so-called endpoint impacts on human health ecosystem quality and resources (Fig. 3). A detailed review of early methods is available in Kounina et al. (2013).

- Impacts on human health
  Impacts on human health by water consumption are addressed by most methods through lack of water for nutrition (e.g. Pfister et al., 2009; Motoshita et al., 2018) and potentially for lack of drinking water (Boulay et al., 2011b). These methods have also been the basis for the consensus method on water-use impacts on human health, which includes water scarcity, economic development and trade effects (Motoshita et al., 2017). Since malnutrition is related to poverty, these models consider socio-economic factors and attribute only a share of the total malnutrition impacts to water scarcity. These models generally have very high uncertainties (Pfister and Hellweg, 2011).

- Impacts on ecosystem quality
  Ecosystems are affected by water use in various ways. The AWaRe method accounts for environmental water requirements (i.e. in-stream flows), but groundwater may also be affected with impacts spread to terrestrial

ecosystems. The recent method of Verones et al. (2017) is consistent with the land-use consensus method by UNEP-SETAC. It combines the biodiversity assessment based on surface and groundwater use on wetlands developed by Verones et al. (2013a,b) with the generic conceptual approach assessing water stress impacts on terrestrial vegetation from Pfister et al. (2009).

- Impacts on natural resources
  Depletion of natural resources is mainly used for fossil and mineral resources. Additionally, stocks of water can be depleted. This mainly concerns groundwater stocks, more specifically fossil groundwater, but can also affect other large water bodies such as lakes, where future impacts are expected due to overuse of water resources. Approaches for assessing these impacts are available in Milà I Canals et al. (2009) and Pfister et al. (2009). Competitive use of renewable water resources is assessed through their consequences on human health and ecosystem quality (see above).

3 Modelling impacts on water quality

The ISO water footprint standard 14046 requires a water footprint to include all impacts on the water resources (i.e. freshwater resources) due to both water consumption and water pollution (from emissions). Water pollution is also sometimes referred to as grey water (Hoekstra et al., 2011), but generally LCA methods assess pollution through different environmental impact indicators such as eutrophication (e.g. from fertilizer emissions) and toxicity (from agrochemicals). These effects are covered in the respective chapters and thus are not further explained here. A guide for assessing eutrophication impacts in livestock systems was published by FAO (2018b), and recommendations from UNEP/SETAC for assessing eutrophication and (eco)toxicity impacts are about to be released (UNEP, 2019).

4 Modelling salinization impacts

Although salinization is a worldwide issue affecting both land and water resources, it has been only partially included in LCA. So far, four indicators have been developed to model salinization impacts in LCA, each one addressing different salinization pathways (Payen et al., 2016). The midpoint soil salinization potential developed by Feitz and Lundie (2002) addresses salinization associated with irrigation water and characterizes impacts on soil structure and the accumulation of sodium in the soil. Amores et al. (2013) evaluated the damages on biodiversity associated with a salinity increase in a Spanish coastal wetland caused by seawater infiltration in the wetland due to groundwater overexploitation for irrigation. Zhou et al. (2013) proposed a method for assessing aquatic ecotoxicity of brine disposal from seawater desalination plants. Leske and Buckley (2003, 2004a,b) developed an LCA salinity impact category for South Africa. They provide salinity potential CFs for salts release in the atmosphere, surface water, natural surfaces and agricultural surface compartments. The main limitations of the existing indicators are their restricted scope in terms of salinization pathways covered (Feitz and Lundie, 2002), their intensive inventory data requirement (Feitz and Lundie, 2002) or their restricted geographical validity (Amores et al., 2013; Feitz and Lundie, 2002; Leske and Buckley, 2003, 2004a,b).

Comprehensively modelling of salinization impacts is complex since it can be due to various types of human interventions (land-use change, irrigation, brine disposal and overuse of a water body), involve both water and soil compartments and can affect human health, ecosystem quality and resources. Payen et al. (2016) proposed a framework for modelling salinization impacts. A bottom-up approach describing the environmental mechanisms (fate, exposure and effect) is recommended because (i) salts and water are mobile and their effects are interconnected, (ii) this approach allows the evaluation of both on- and off-site impacts and (iii) it is the best way to discriminate systems and support a reliable eco-design approach.

5 Soil quality and land-use implications

The availability and quality of freshwater is closely related to soil quality. Indicators of soil quality include soil organic carbon, biotic production, erosion, mechanical filtration, groundwater regeneration and water infiltration capacity. Soil organic carbon has often been considered as a good indicator for overall soil quality (Milà I Canals et al., 2009; UNEP, 2019).

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The land-use indicator model LANCA (Bos et al., 2016) estimates the infiltration capacity and groundwater regeneration due to different types of land use as an important indicator. Land use affects soil sealing and thus soil permeability, groundwater recharge and surface water flows. Soil quality and land use also affect the eutrophying impacts of soil erosion (Scherer and Pfister, 2015).

6 Accounting for geographical and temporal variation

Water is mainly a flow resource and the flows vary over time. Additionally, water is not a tradable good in general (although it is the most extracted resource) and thus humans rely on local water availability (as is obviously the case for natural ecosystems). This special case of freshwater resources requires geographically and temporally explicit inventory and impacts assessment modelling for agricultural systems, as described in Section 2.

AWaRe and other recent water scarcity methods thus account for monthly and watershed characteristics (refer to Section 7.1 for an illustrative case study). Since water scarcity is modelling the impact of a resource flow, temporal fluctuations are important, especially since in general scarcity is the highest during peak demand. This also applies to variability due to extreme weather periods or events. A prominent example was the 2018 summer in Europe, where even in generally water abundant locations such as Switzerland, water scarcity led to bans on water use for agriculture, when agriculture needed irrigation due to the extremely dry and hot spring/summer (which is not common). While climate change trends can be observed, the variability of weather and especially precipitation events contribute to modelling uncertainty. This applies especially for forecasting, which is evident from the low consistency of precipitation forecasts for the 2050s by different climate models (IPCC, 2007).

Another important aspect that contributes to variability in agricultural production and thus high uncertainty in generic assessment are crop yields. Yields are affected by pests and management failures, which vary over time and space.

7 Case studies

7.1 Spatio-temporal resolution matters in water scarcity footprinting: case study of New Zealand milk

A case study on milk production in New Zealand illustrates the importance of geographical and temporal variation when modelling impact on water scarcity (Payen et al., 2018). This case study estimated the water scarcity footprint of milk produced in two contrasting regions in New Zealand: 'non-irrigated moderate rainfall' (Waikato) and 'irrigated low rainfall' (Canterbury). An extensive inventory of all the consumed water flows was carried out from the production of dairy farm inputs to the milk and meat leaving the dairy farm, including the water uses on farm (e.g. irrigation water, cow drinking water …). Impacts were calculated with the widely used Pfister et al. (2009) indicator, as well as methods recommended by the UNEP/SETAC Life Cycle Initiative (AWaRe and Motoshita et al., 2017) for water scarcity and human health impacts. Different spatial (country vs. region) and temporal (annual vs. monthly) resolutions were tested (for the inventory flows and CFs). Results showed that the water scarcity footprint decreased by 74% (Waikato) and 33% (Canterbury) when regional and monthly CFs were used instead of country and annual CFs, clearly demonstrating that using aggregated CFs may overestimate impacts. However, in other cases, aggregated CFs might underestimate the impacts (Pfister and Bayer, 2014). In particular, it is interesting to note that spatial resolution had a major effect on the water scarcity footprint of Waikato milk from non-irrigated pasture (i.e. localizing the farm in a specific catchment had more effect than accounting for the timing of water consumption). In contrast, temporal resolution had a major effect on the water scarcity footprint of Canterbury milk from irrigated pasture (i.e. accounting for the timing of water consumption for irrigation had more effect than specific farm location). The water scarcity footprint calculated at the higher resolution was 22 L_{world} eq/kg FPCM for Waikato milk and 1118 L_{world} eq/kg FPCM for Canterbury milk. Regarding the contribution analysis, background processes such as fertilizer manufacturing dominated for non-irrigated pasture, but was negligible for irrigated pasture where irrigation dominated the impacts.

7.2 Life cycle assessment of a perennial crop including an in-depth assessment of water-use impacts: the case of mandarin in Morocco

Mandarin production in the water-scarce Bahira plain in Morocco is an interesting case study illustrating (i) the challenge of perennial crop modelling in LCA, (ii) high valuable crop production in a water-scarce area and (iii) cultivation of a crop sensitive to salinity in an area prone to high soil salinity. Indeed, in this area the pressure on the water resource is worsened by salinity of the aquifer. The 25-year perennial crop cycle of a large commercial mandarin orchard (8-year old) was modelled from nursery to end-of-life, based on primary farm data and a projection scenario. The life cycle of the mandarin was modelled up to the French market, accounting for post-farm production stages and transportation from Morocco to France. To satisfy the water inventory requirements for a perennial crop, we had to develop and use a model of field water flows: estimating the consumed and released water flows according to actual water supply and system specificities (soil-climate-practices). Both water and salt elementary flows were estimated and used for modelling impacts on water scarcity. Impacts were calculated using Pfister et al. (2009) methodology and impacts on water scarcity stress/availability (associated with both consumptive and degradative water use) were calculated using the Boulay et al. (2011a,b) method. Other impact indicators were assessed, including climate change, eutrophication, (eco)toxicity and acidification. Results for the contribution analysis showed the dominant contribution of energy required for pumping water from the aquifer, revealing a water-energy nexus (Fig. 4). Indeed, mandarin cultivation requires a lot of water that has to be withdrawn from a deep aquifer, thus requiring the use of electricity-intensive pumps. In addition, over 50% of the Moroccan electricity mix is from fossil energy. This water-energy nexus is frequent in water-scarce

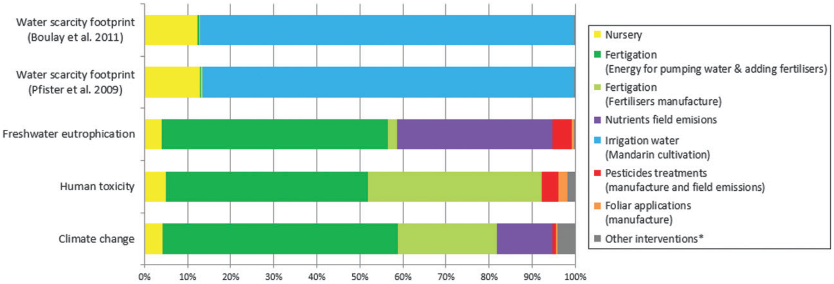

Figure 4 Contribution analysis of a mandarin crop from Morocco at the farm gate: Environmental impacts were calculated with ReCiPe (H), Boulay et al. (2011b) and Pfister et al. (2009). *Other interventions include orchard establishment, fertigation (materials), mechanical weeding and wood grinding, pesticide treatments (water, materials, energy), foliar applications (energy) and fruit harvesting (energy and materials).

countries, and was also observed for clementine (Basset-Mens et al., 2016) and tomato (Payen et al., 2015). Without surprise, irrigation was the dominant contributor to water scarcity and availability impacts. Water availability impacts calculated with Boulay et al. (2011a,b) were close to water scarcity impacts estimated with Pfister et al. (2009), respectively 181 m^3.ton^{-1} and 189 m^3.ton^{-1} mandarin at the farm gate. Water salinity inventory was accounted for in water stress/availability impacts, but in the absence of an operational indicator for salinization, impacts associated with soil and water salinization could not be addressed (Payen, 2015).

7.3 Water conservation and increased irrigation efficiency can add to water scarcity: the case study of drip irrigation

Drip irrigation is an important technology to save unproductive evaporation and increase water-use efficiency. As described in the study of Ward and Paulido-Velazquez (2008), increased water-use efficiency can lead to additional production and due to reduced return flows through infiltration, overall water scarcity can be increased. Ward and Paulido-Velazquez (2008) performed an integrated basin-scale analysis by assessing biophysical, hydrologic, agronomic, economic, policy, as well as institutional aspects of the Upper Rio Grande Basin of North America. They concluded that water use is unlikely to be reduced by water conservation subsidies and that more efficient irrigation technologies reduce water return flows and aquifer recharge. Additionally, reduced return flows can lead to soil salinization (e.g. Contreras et al., 2017). Therefore, it is important that water efficiency policies account not only for water-use reductions, for example through drip irrigation, but also monitor and reward reduced water depletion. Conservation programmes should also account for salinization risks.

8 Summary

8.1 Optimizing freshwater efficiency

Effects of water on productivity is a well-known field in agricultural research and various tools to improve it exist. In an LCA or water footprint assessment, it is important to first localize the hotspots of water use, since often it is in the supply chain. Further research needs to provide better tools to assess hotspots of impacts accounting for uncertainty, since the supply chain data is often not detailed in standard assessments. In the longer term, benchmarks should be established to identify the improvement potential in combination with relevance among the thousands of processes generally involved in an LCA or water footprint study to most effectively improve the production system.

8.2 Optimizing effective use of water resources

Effective use of water (such as irrigating high-value crops) is more important than water-use efficiency. This is especially important in agriculture, since biomass products can often be replaced. The major purpose – food supply – can be achieved by cultivating a variety of crops and livestock. Diet changes have been identified as having a high potential to reduce water scarcity. For example, the replacement of animal-based with plant-based protein is often considered as an alternative for reducing global blue water consumption (Jalava et al., 2014). However, when analysing such dietary changes, it is crucial to account for differences in the nutritional value and for balanced diets (which may be difficult to assess comprehensively). There are also alternative options for producing much less water-intensive fibre and biofuel products, although often at the expense of other environmental impacts. Systems analysis is therefore important to optimize agricultural production systems. While effective water use and choice of products can be strategies to reduce all impacts, it can have a greater effect on water scarcity assessments, since large-scale reduction in water consumption can also lower water scarcity indicators.

Food losses have a large impact on water scarcity, not only as part of the agricultural production, but even more importantly through the processing and consumer phases of agricultural products. A recent study showed the high potential of combining the different mechanisms of avoiding food waste with increased agricultural efficiency, but also revealed that more detailed research is required in the future (Kummu et al., 2017).

8.3 Minimizing environmental impacts of water consumption

Water consumption in different locations can lead to highly varying environmental impacts. Therefore, the efficient and effective use of water should also be linked with reducing environmental impacts. This includes accounting for the hydrology of the system as well as the vulnerability of humans and ecosystems. Although indicators are still being improved, all the recent developments in water-use impact modelling are a major contribution towards accounting for catchment specificities and seasonality. Thus, current trends in research acknowledge that the same quantity of water used may have very little or huge consequences depending on where and when it was consumed.

Reducing impacts of water consumption may affect other impact categories such as soil quality, soil and water salinization and toxicity. These impacts, which might also come with a trade-off in water scarcity impacts, need to be captured (i.e. potential burden shifts identified) by doing a multi-criteria analysis in LCA. However, some impact indicators are not yet operational (e.g. salinization) and might need to be assessed in a more qualitative way. Operationalizing CFs for these related impacts to quantify the impacts along supply chains is needed to assess water impacts in a comprehensive way.

8.4 Global dimension of water scarcity

While water scarcity is a local problem, the cause is often international due to the globalized economy. Food products are heavily traded and impacts occur often far away from consumption of the products, and thus national and international policy actions are required (IRP, 2019). While trade might alleviate water scarcity, it can also increase water stress, since trade mainly reflects affluence, rather than water scarcity (Weinzettel and Pfister, 2019). Thus, policies have to account for the economic aspects related to water scarcity in regions with low economic development.

Companies have a large influence on trade; thus, it is important to involve them in coordinating actions to prevent water scarcity. Recently, the concept of science-based targets has emerged. The goal is that companies set reduction goals based on scientific knowledge, which then get evaluated and eventually approved. Several large companies are making progress in this direction (SBT, 2019). So far, most focus has been on climate targets, but water scarcity has gained interest too, together with land use, pollution of oceans and biodiversity. Global policies such as the Paris Agreement to combat climate change might be necessary to address water scarcity on a global level.

9 Future trends in research

9.1 Impact assessment

Assessing the environmental impact of water consumption is still a relatively young research field and several gaps have been identified. The main methods do not distinguish groundwater and surface water, which have distinct hydrological behaviour and different values for humans and ecosystems. The main reason is that global hydrological models are very weak on groundwater and data on the state of groundwater are rather scarce. Therefore, recommendations of an international working group on water-use impacts in LCA are to create a more detailed model to better assess impacts on ecosystems (Nunez et al., 2018).

There is a methodological gap in the interaction of water use with other environmental impacts, such as assessment of salinization impacts (see Section 4 for more details). Efforts should focus on the development of operational indicators addressing impacts on soil and water. Modelling salinization impacts comprehensively is a challenge since it is strongly dependent on water availability, water and soil quality/composition.

9.2 Inventory

Agriculture consists of hundreds of millions of individual producers and thus inventory assessment requires special attention to variability and if possible to local assessment of production. We often make the distinction between conventional vs. organic production systems, but there are hundreds of agricultural management alternatives in a given pedo-climatic environment. In a context where the Global Agronomy concept is emerging (e.g. Makowski et al., 2014), we need to capture all system specificities with a global coverage. Remote sensing data are a promising basis in that regard and enable presentation of results at a high temporal frequency across large spatial areas. But using such data raises the challenge of their management and interfacing with analysis tools or LCA software. With the increasing use of spatially explicit data (both for the inventory and impact assessment), there is future requirement for models and LCA software to supporting a coupling with GIS. This coupling with GIS is already possible with the agro-hydrological model AquaCrop (inventory of water flows) and the LCA software Open LCA (life cycle modelling and impact assessment) as well as the scientific open-source LCA software Brightway, as summarized by Frischknecht et al. (2019). Additional information on inventory modelling is provided by the guidelines for assessment of water use of livestock production systems and supply chains by FAO (2018a).

9.3 Technical solutions

From hunters to rainfed and irrigated agriculture, humankind invented many technical solutions to enhance agricultural output. Beyond drip irrigation, greenhouse production can increase yield and thus water productivity significantly. Further research on where production can reduce pressure on water resources directly or through replacing other production locations is important to provide better knowledge on how to improve sustainability of the food production system. Other trends in research include urban gardening, which involves technical innovation and symbiosis with industrial systems.

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11 Where to look for further information

In recent years, many research papers have been published and an extensive review is beyond the scope of this chapter, as it would also be outdated soon. However, beyond the references in the sections above, there is a list of papers, reports and book chapters that address the topic of water use in LCA and water footprinting in higher detail.

The FAO LEAP report gives the most recent summary of water-use assessment in agriculture, including water productivity, water footprint and LCA research. The draft report is publicly available (FAO, 2018a). There has also been exchange on general discussion about the water footprint concepts and different applications (Pfister et al., 2017; Hoekstra, 2016).

Three book chapters on water use in LCA and water footprinting are useful resources to get more details on LCA methodologies and applications, even if latest scientific developments are missing (Pfister, 2015; Berger et al., 2016; Verones et al., 2016).

In terms of impact assessment, the international harmonization efforts towards a consensus method for water scarcity (midpoint, Boulay et al., 2017) and human health impacts (endpoint, Motoshita et al., 2017) were reported by UNEP in 2017. Recommendations for assessing impacts related to water quality (eutrophication and ecotoxicity) are about to be released (UNEP, 2019).

UNEP's international resource panel (IRP) published two reports dedicated to water use related to resource and material production (UNEP, 2012, 2015).

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AQ: Please confirm the reference "SBT (2019)" is set as correct.

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