frontiers in Sustainable Food Systems

REVIEW
published: 17 April 2020
doi: 10.3389/fsufs.2020.00035

Agriculture's Historic Twin-Challenge Toward Sustainable Water Use and Food Supply for All

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A sustainable and just future, envisioned by the UN's 2030 Agenda for Sustainable Development, puts agricultural systems under a heavy strain. The century-old quandary to provide ever-growing human populations with sufficient food takes on a new dimension with the recognition of environmental limits for agricultural resource use. To highlight challenges and opportunities toward sustainable food security in the twenty first century, this perspective paper provides a historical account of the escalating pressures on agriculture and freshwater resources alike, supported by new quantitative estimates of the ascent of excessive human water use. As the transformation of global farming into sustainable forms is unattainable without a revolution in agricultural water use, water saving and food production potentials are put into perspective with targets outlined by the Sustainable Development Goals (SDGs). The literature body and here-confirmed global estimates of untapped opportunities in farm water management indicate that these measures could sustainably intensify today's farming systems at scale. While rigorous implementation of sustainable water withdrawals (SDG 6.4) might impinge upon 5% of global food production, scaling-up water interventions in rainfed and irrigated systems could over-compensate such losses and further increase global production by 30% compared to the current situation (SDG 2.3). Without relying on future technological fixes, traditional on-farm water and soil management provides key strategies associated with important synergies that needs better integration into agro-ecological landscape approaches. Integrated strategies for sustainable intensification of agriculture within planetary boundaries are a potential way to attain several SDGs, but they are not yet receiving attention from high-level development policies.

Keywords: sustainable development goals, environmental boundaries, social boundaries, food security, water management, environmental flow requirements, sustainable intensification

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Specialty section:
This article was submitted to
Water-Smart Food Production,
a section of the journal
Frontiers in Sustainable Food Systems

Received: *31 December 2019*
Accepted: *11 March 2020*
Published: *17 April 2020*

Citation:
Jägermeyr J (2020) Agriculture's Historic Twin-Challenge Toward Sustainable Water Use and Food Supply for All.
Front. Sustain. Food Syst. 4:35.
doi: 10.3389/fsufs.2020.00035

1. A CHALLENGE FOR HUMAN INGENUITY

1.1. Conundrums of Settled Life

Agriculture is the foundation of all cultures. The defining characteristics of human rise are two major transitions, the Neolithic revolution (10,000–5,000 yr BP) and the Industrial Revolution (1,700–2,000 yr AD) (Harari, 2014; Schellnhuber, 2015). Through the prehistoric shift from foraging to farming—humans learned to domesticate plants and animals for food, livestock as a labor substitute, and invented storage—humanity tipped the comparative advantage and entered Neolithic times, which sustained larger human populations and might form the largest historical step-up in human culture (Grigg, 1974; Diamond, 2002). Thereby freed up human capital was the cornerstone of sedentism and elaborate social systems (nations, credit, markets, advanced communication), key to early cities (Weisdorf, 2005). Since its very beginning, quandaries in food availability have characterized human development. But with the capacity of social learning and building knowledge across generations, human societies have implemented—first by chance or trial and error—a long series of ingenious achievements to nourish their ever-increasing populations (Henrich and McElreath, 2003; De Fries et al., 2012). Maintaining soil fertility (e.g., through human manure, and later guano, and ground animal bones), introducing new crops (e.g., the potato's ascent as a staple in Europe), and the ancient trick to defeat water limitation (qanats, rainwater harvesting, and irrigation systems) set the scene for the race between food production increase and population growth: human populations grew to 900 million by 1800 (Grigg, 1974; Postel, 1999; Ellis, 2011). Mankind has settled down and the question changed from how much space a given number of people need for self sufficiency—in Paleolithic times people hunted and gathered over vast areas—to how many people can live off a given piece of land (Schellnhuber, 2015).

The second major agricultural upswing occurred in the course of the industrialization of England, ignited around 1800 and spreading quickly around the world. Pivotal innovations in technology such as an improved version of the Chinese iron plow and the seed drill, paired with land enclosure and new crop rotation systems, increased agricultural production dramatically and are seen as a cause of the Industrial Revolution across sectors (Thomas, 2005; DeFries, 2014). Subsequently, the industrial fixation of inorganic nitrogen (proliferation of the Haber-Bosch process), and the replacement of human and animal labor with fossil fuel, accompanied by major increases in life expectancy, fueled a population explosion and far-reaching demographic upheaval. By the mid of the 19th century only 20% of the population employed in the agricultural sector could free 80% of human capital to forge ahead with other sectors (Grigg, 1974).

Although populations doubled over the past 50 years, to now almost 7.5 billion (Population Reference Bureau, 2016), the latest "pivot" (DeFries, 2014) of agricultural industrialization—the Green Revolution—was capable of tripling stable crop production with only a 30% increase in cultivated land area (FAO, 2002; Pingali, 2012). Propelled by Norman Borlaug, a large-scale program of plant breeding (high-yielding varieties such as hybrid corn and dwarf wheat, but also shortening of the growing period), modern agricultural systems (mechanization and rigorous application of chemical fertilizer), and above all, the systematic expansion of irrigation, improved especially wheat yields significantly (DeFries, 2014). From Mexico spreading to Pakistan, India, and other countries, food security greatly improved and millions of people were saved from starvation, most notably in the developing world. The amount of food produced surpassed the amount required for each person and resulting decreased prices dramatically improved energy and protein consumption, much for the poor, but even at global scale from 2200 $kcal\ cap^{-1} d^{-1}$ in 1960 to 2700 $kcal\ cap^{-1} d^{-1}$ in 2000 (IFPRI, 2010). This success rests upon concerted investments in agronomic research, infrastructure, and market development. Most importantly, however, it would not have been realized without large-scale water appropriations for irrigation from new and often nonrenewable sources (Postel, 1999; Cassman and Grassini, 2013).

The ever-expanding quest to feed human populations did not come without repeated devastating setbacks. Settled life, dense populations, and stratified societies gave rise to crowd diseases, conflicts, and famines (Diamond, 2002). For instance, during Ireland's Great Famine in the 1840s potato blight attacks ravaged the nationwide dependency on a single potato variety—Ireland's population fell by 25% (Curran and Fröling, 2010). In the long run, though, mankind developed solutions and proved successful to stretch continuously the number of people to survive. However, the question if human ingenuity will proceed to circumvent future quandaries in the tightening water-food nexus toward future food security keeps alive a long-running dispute.

1.2. Growing Societies in Face of Environmental Limits

The bottleneck of planetary finite resources has been recognized already by Thomas R. Malthus in the late eighteenth century, who predicted catastrophic side effects with humanity's expansion (Malthus, 1798). Since then the paradigm of supposedly inevitable "limits to growth" fostered prominent support (e.g., Ehrlich, 1968; Meadows et al., 1972). This worldview is contested by Julian Simon, the classic protagonist of the theory that technological and social progress will not only continue to stretch food abundance, but make it infinite—the ultimate resource would therefore not be oil or water, but human ingenuity (Ruttan, 1971; Simon, 1981). Both beliefs, however, prove incapable of describing historical broader perspectives. The Neo-Malthusian (Aligica, 2009) score of dire predictions of famine underestimate the ability of human societies to adapt and change, and thus overcome chronic food deficiencies as demonstrated by the actual course of history—Julian Simon won on the bet against Paul Ehrlich (Sabin, 2013). But Simon's complacent idea that people are resource creators, not destroyers, neglects already profound and potentially irreversible human alterations of Earth-system functioning (Millennium Ecosystem Assessment, 2005). With the need to provide food, anthropogenic forces transformed the terrestrial biosphere, from mostly natural landscapes to predominantly anthropogenic biomes (**Figure 1A**). By the year 2000, 39% of ice-free land surface were turned into agricultural land or settlement, and only 25% remain natural (Ellis et al., 2010). This has critical implications for the diversity, composition, and life-supporting functioning of global ecosystems, and is not least a significant contributer to climate change (e.g., Tilman, 1999; Foley et al., 2005; Barnosky et al., 2011; Hartmann et al., 2013; Campbell et al., 2017). Although the Green Revolution-driven intensification held back more extensive land conversion to agriculture (Stevenson et al., 2013),

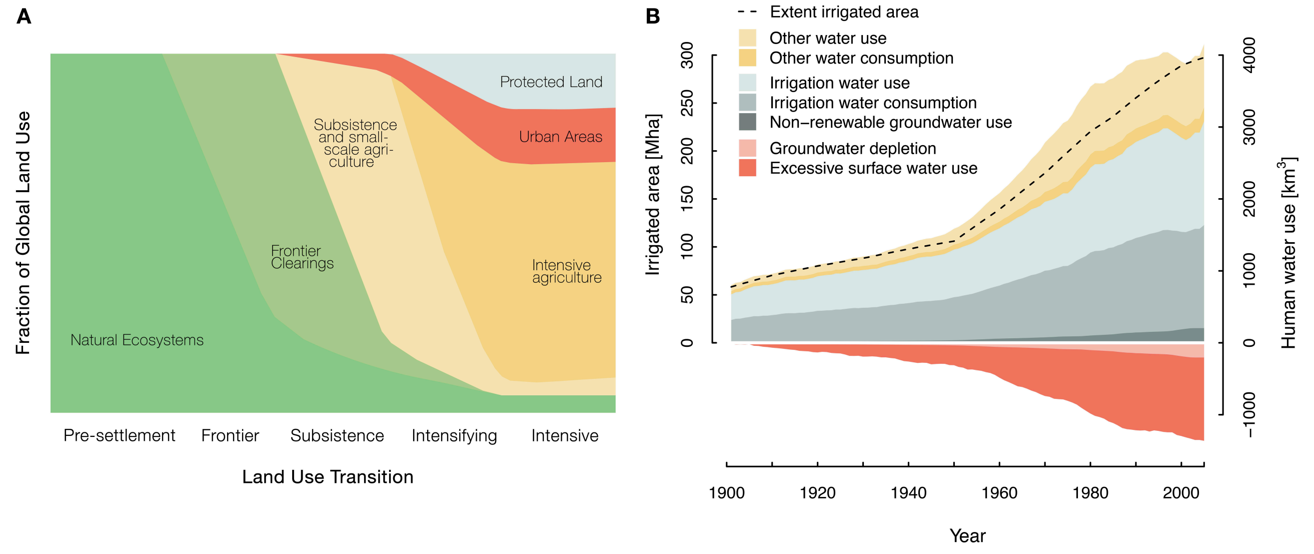

FIGURE 1 | Historical transitions in human land and water use. **(A)** Shows schematic stages of historical anthropogenic land-use transitions (redrawn from Foley et al., 2005). Over the course of the 20th century, **(B)** shows the expansion of areas equipped for irrigation (dashed line, left axis; based on Siebert et al., 2015) along with absolute amounts of human water use and consumption (colored wedges, right axis). Water use and consumption (i.e., a fraction of water use) is separated for irrigation (own model simulations) and other sectors including industrial, domestic, and livestock (based on Flörke et al., 2013). Non-renewable groundwater use is based on simulations from Wada et al. (2016b). Unsustainable water use, that is, the transgressions of environmental flow requirements and non-renewable groundwater use, is highlighted as negative volumes (see the **Appendix** for LPJmL model simulation details).

it came at the cost of profound environmental consequences (Pingali and Rosegrant, 1994). Monocultures accompanied with chemical fights against evolving pests and diseases impair biodiversity and human health (Eddleston et al., 2002; Goulson et al., 2015). More synthetic fertilizer is applied in agriculture than is fixed naturally in all terrestrial ecosystems together, with widespread effects on water quality and coastal and freshwater ecosystems (Smil, 1991; Galloway and Cowling, 2002; Mekonnen and Hoekstra, 2015). Among the most pervasive factors, freshwater depletion, dam construction, and river diversion—in the first place to quench the thirst of irrigation (**Figure 1B**)—have transformed the hydrologic cycle of the Earth to the degree that approximately 25% of the world's major rivers no longer reach the ocean (Gleick, 2003; Molden, 2007). The extent of the world's wetlands has collapsed to one third (Gardner et al., 2015), and half of all accessible freshwater is used for human needs (Postel et al., 1996; Vörösmarty et al., 2005).

The Holocene provides a stable and largely benign environment for humanity, but agricultural intensification became a local to global driver of critical influences on Earth-system processes (Matson, 1997; Foley et al., 2005; Millennium Ecosystem Assessment, 2005; IAASTD, 2009; Campbell et al., 2017). Humans emerged as a planetary force, which is considered as a new geologic epoch, the Anthropocene (Crutzen, 2002), increasing the risk to push the Earth system into a post-Holocene state with characteristics that potentially undermine system resilience and human well-being (Monastersky, 2015; Steffen et al., 2016). Such risks have been acknowledged by defining critical environmental limits to anthropogenic influences on the Earth system (e.g., Petschel-Held et al., 1999; Lenton et al., 2008), formulated later as "Planetary Boundaries" (Rockström et al., 2009). As a precautionary principle, the nine Planetary Boundaries—absolute biophysical thresholds or limits—delineate the safe operating space for humanity, and thus sustainable long-term prosperity (Steffen et al., 2015). Although such numbers are difficult to quantify and to some degree still lack conceptional scrutiny, the concept marks actionable policy targets and thus provides a valuable tool for planetary stewardship. The central evidence of the framework is clear and striking: (i) there is only marginal room for additional expansion and conventional intensification of agriculture, and (ii) current over-exploitation must be reset to maintain future capacities for human development.

1.3. The Twin-Challenge: People and Planet

Not all countries benefited equally from historic resource use and intensification, severe disparities in human deprivation remain. As of today, more than 2 billion people are affected by water stress, which hinders economic and social development (ECOSOC, 2016a). Mainly as a result of vulnerable and low-yielding farming systems, 800 million people remain chronically undernourished, 160 million children suffer stunted growth, and >10% of the world's population still live in extreme poverty (<US\$1.90 $cap^{-1}d^{-1}$) (FAO et al., 2015; ECOSOC, 2016a). Such realities underline that agriculture is still at the center of sustainable development (Brundtland Commission, 1987), even though it is clear that tackling hunger and malnutrition is not only about the amount of food produced.

Sustainable development in the Anthropocene takes more than environmental sustainability. Equally important are social and economic foundations for human development (Tibbs, 2011; Raworth, 2012b; Griggs et al., 2013). Raworth (2012a) added such social boundaries to the Planetary Boundary concept, creating a non-trivial subspace, the "safe and just space for humanity." The right to food therefore depends on environmental integrity (World Social Science Report, 2016). **Figure 2A** illustrates this idea for the two dimensions food production and water use (i.e., water withdrawals), providing the conceptual framing for this article.

In the vein of integrating social needs and environmental limits, a set of Sustainable Development Goals (SDGs) was stipulated by the United Nations in September 2015 (United Nations, 2015a). The 2030 Agenda for Sustainable Development—relevant to developed and developing nations alike—is a transformative and ambitious global vision for sustainability, eradication of hunger, and poverty. As a follow-up of the partly successful Millennium Development Goals[1], they now focus more prominently on environmental integrity, integrating the three dimensions of sustainable development: nested environmental, social, and economic sustainability, based on closely interwoven goals and targets (ICSU, 2015). This new direction—integrating people and the planet—is an important step forward as the SDGs now acknowledge that food, livelihoods and natural resource management can no longer be looked at separately (FAO, 2016). They stipulate a sustainable and resilient food production system (target 2.4) and sustainable water withdrawals (target 6.4) as agreed goals among all nations. On the same page, however, target 2.3 aims at doubling both agricultural productivity and incomes of smallholder farmers by 2030, in support of target 2.1, that is, hunger eradication and food security. This lays out a bold and seemingly conflicting agenda. Although there was effort in providing an indicator framework for progress monitoring (ECOSOC, 2016b), many of the environment-related targets and indicators are insufficiently defined, not backed by available data, and remain vague (Griggs et al., 2014; ECOSOC, 2016b).

The strong rise in the human population is likely not to level off until 2050, by which time it is expected to have reached 9–10 billion (UNFPA, 2013; United Nations, 2015b). The unprecedented confluence of socio-economic global mega-trends such as economic growth and urbanization lead to substantial changes in consumption patterns and more varied, high-quality diets and thus resource requirements. This results in suggestions that crop calorie production needs to be increased by 60-100% in the forthcoming decades to eradicate hunger (IAASTD, 2009; Alexandratos and Bruinsma, 2012; Valin et al., 2014; Searchinger et al., 2018). Competition for water, land, and energy will intensify, which further complicates the challenge of closing the global food gap and will test the resilience of local to global food systems (Godfray et al., 2010; Foley et al., 2011; Foresight, 2011; Searchinger et al., 2013). The current slowing down of historic yield increases (Ray et al., 2012) is expected to face adverse impacts through unabated climate change, which is likely to exacerbate food insecurity particularly among the poorest by increasing water stress and hydro-climatic variability (Lobell

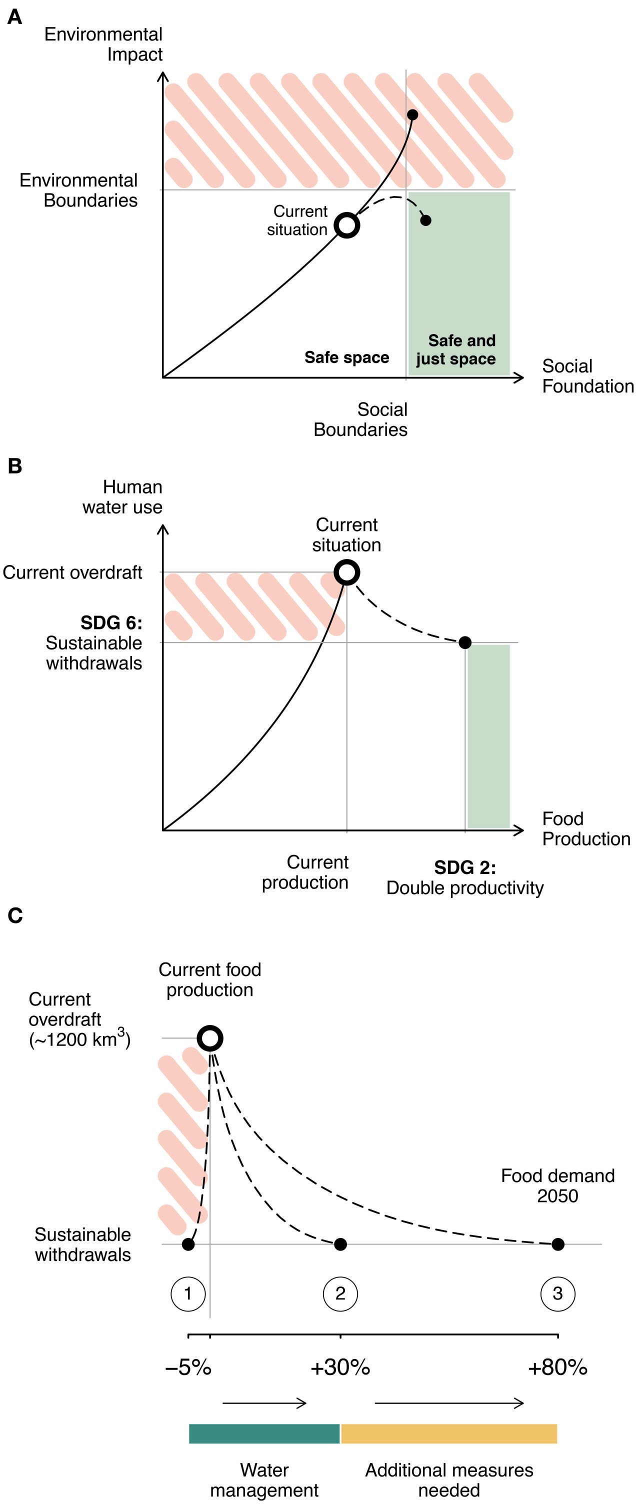

FIGURE 2 | Farm water management as a key factor in bridging the water-food gap. **(A)** Illustrates the concept of the safe and just operating space for humanity delineated by an environmental and social boundary. The environmental boundary is illustrative for various Planetary Boundaries, such as freshwater use, land use, or climate change. The social boundary marks the threshold of an agreed social foundation. Pathways going beyond the

(Continued)

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[1] The target of global poverty reduction was reached five years ahead of schedule, yet more than a billion people still live in extreme poverty today. Shortfalls remain in achieving the targets related to food security (United Nations, 2016).

FIGURE 2 | current situation highlight a conventional resource-based (solid line) and a sustainable intensification option (dashed line). **(B)** Details the same concept for the water–food case explicitly and outlines the pathway envisioned in the 2030 Agenda for Sustainable Development, i.e., resetting current freshwater overdraft while simultaneously doubling agricultural productivity. **(C)** quantifies effects on global caloric food production when policies in line with sustainable withdrawals (SDG 6) were implemented. Option 1 rigorously maintains EFRs (based on Jägermeyr et al., 2017); option 2 additionally exploits farm water management opportunities (see **Appendix**); option 3 incorporates additional measures such as soil fertility management, additional irrigation expansion, and food waste reduction to close the food gap by 2050 (e.g., Gerten et al., 2020).

et al., 2008; Wheeler and von Braun, 2013; Cisneros et al., 2014; Porter et al., 2014; Rosenzweig et al., 2014). Climate change might further limit the potential for intensification of production (Pugh et al., 2016), paired with the present degradation of ecosystems, poses a threat to the long-term sustainability and the potential reprint of the Green Revolution's success (Pingali, 2012).

With humans established as a planetary force, the question is: Does a safe and just space for humanity exist, as delineated by the complex line of SDG targets? Under which conditions does it exist, and how would a viable path look like to reach it? After all, achieving global food security against a background of climate change and increasingly scarce freshwater resources, without jeopardizing Earth system functioning (**Figure 2A**), remains one of the grand challenges for the twenty first century (e.g., Tilman et al., 2002; Foley et al., 2011; Godfray and Garnett, 2014; Rockström et al., 2017; Searchinger et al., 2018).

2. WATER AS KEY FACTOR: BETWEEN SCARCITY AND OPTIMISM

Freshwater contributes fundamentally to human well-being and to the resilience of social-ecological systems. While maintaining ecosystem functions, water is inextricably linked to poverty reduction, economic growth, food security—and therefore at the very core of sustainable development (World Water Assessment Programme, 2015b). Water is central to attaining most, and arguably all, of the SDGs (ECOSOC, 2016a). It comes down to water, because global freshwater resources are scarce and heterogeneously distributed across populations and inequalities exist in water access (Carr et al., 2015; Mekonnen and Hoekstra, 2016). Between 1960 and 2005, the percentage of the world population under chronic water stress ($<1{,}000\ m^3/cap/yr$) increased from 9% to 35% (Kummu et al., 2010). As the total freshwater demand across sectors to meet SDG targets (SEI, 2005; World Water Assessment Programme, 2015b) is projected to increase by a global 55% by 2050, in some countries even by 100%, global freshwater resources are put under progressive pressure (Vörösmarty et al., 2005; Gleick and Palaniappan, 2010; Flörke et al., 2013; Cisneros et al., 2014; Porkka et al., 2016). In the end, due to its complex and trans-boundary nature, freshwater resources may be regarded as even more valuable than oil—which comes with alternatives, but water might not (Kabat, 2013).

In view of the SDG agenda, agricultural water use stands out twice. First, over-exploitation and pollution of global freshwater resources is the number-one reason to the degradation of ecosystems, with far-reaching consequences across the world. Effective means to reset overuse and conserve, protect, and enhance aquatic ecosystems at larger domains are yet to be identified. Second, freshwater is an irreplaceable element of growing food. Worldwide doubling of agricultural productivity appears beyond reach without a profound revolution in agricultural water management. The SDG agenda confidently builds upon opportunities associated with water management in both irrigated and rainfed agriculture that, however, are yet to be devised (**Figure 2B**).

2.1. Irrigated Farming—Ratchet and Hatchet

Irrigation expansion was a major contributor to the Green Revolution, especially in Asia. Over the last 50 years irrigated area roughly doubled (Siebert et al., 2015; FAO, 2017) and today a quarter of total harvested cropland is under irrigation, producing ∼40% of global cereals (Portmann et al., 2010). Irrigation heavily sustains global agricultural production and contributes to food security worldwide. But it comes at a steep price for the ecosystem. Irrigation is the single largest user of freshwater, accounting for roughly 70% of total withdrawals, and over 90% in the world's least-developed countries (Gleick et al., 2009; World Water Assessment Programme, 2015a). Water resources are increasingly depleted for human needs, not only, but most importantly for irrigation. In some regions withdrawals exceed 100% of renewable water resources, with devastating consequences (Postel, 1999). Groundwater is being depleted to the degree that it contributes to sea level rise in a non-trivial way (Aeschbach-Hertig and Gleeson, 2012; Pokhrel et al., 2012; Wada et al., 2012a). Wetlands disappear irreversibly, many rivers no longer reach the ocean or inland sinks, and in turn 20% of the global irrigated land area is affected by salinization, waterlogging occurs, water quality deteriorates (Mekonnen and Hoekstra, 2015), and invasive species are introduced and proliferate (Vörösmarty et al., 2005; Molden, 2007; FAO, 2011; Wada et al., 2012b). Overall human water use consistently rose over the course of the twentieth century, now exceeding 4,000 km^3/yr (**Figure 1B** and **Table 1**), roughly 3,000 km^3/yr for irrigation and 1,000 km^3/yr for other sectors; estimates vary across studies (see e.g., Flörke et al., 2013; Wada et al., 2016a; Huang et al., 2018). Aquatic ecosystems are thereby rapidly degrading with potentially serious but unquantified costs, imposing the risk of regime shifts away from stable environmental conditions (Vörösmarty et al., 2010; Rockström et al., 2014). Safeguarding riverine and estuarine ecosystems is imperative for sustainable development as they provide life-supporting functions (United Nations, 2015a) that, in turn, depend on maintaining Environmental Flow Requirements (EFRs), the quantity, timing, and quality of river flows (Acreman and Dunbar, 2004; Falkenmark et al., 2004; Millennium Ecosystem Assessment, 2005; Brisbane Declaration, 2007) and groundwater (de Graaf et al., 2019).

The Planetary Boundary for human freshwater use is defined as the maximum global amount of freshwater that can be appropriated by humans (i.e., blue water consumption abstracted

TABLE 1 | Food production and water use under different water management scenarios.

	Food production	Irrigation withdrawal	Irrigation consumption	Other sectors withdrawal	Other sectors consumption
Current situation	740 * 10^{13} kcal	2,409 km^3	1,255 km^3	1,070 km^3	193 km^3
1. Respect EFR	−5%	−41%	−35%	−22%	−22%
2. Respect EFR with ambitious water management	+30%	−50%	−24%	−24%	−25%

*"Respect EFR" refers to a world in which water withdrawals are not allowed to tap into environmental flows (based on Jägermeyr et al., 2017). "Ambitious water management" refers to a management scenario with best-practice irrigation upgrades (including irrigation expansion with water saved through efficiency improvement), supplemental irrigation through water harvesting, alleviation of soil evaporation (mulching, conservation tillage); management assumptions are based on Jägermeyr et al. (2016), but new simulations are presented here to be combined with the "Respect EFR" scenario (see **Appendix**). Scenario 1 and 2 are illustrated in **Figure 2C**. Data are averaged for the 1980 to 2009 time period. For similar estimates based on an independent method see e.g., Rosa et al. (2018).*

from rivers, reservoirs, lakes, and aquifers) (Rockström et al., 2009; Steffen et al., 2015). Provisionally set to 4,000 km^3/yr (note that consumption does not equal withdrawals, see below), it builds upon a top-down approach that juxtaposes global renewable freshwater resources and water volumes needed to avoid water stress, treated as a global average. Despite the significance of this initial quantification, it oversees local impairments and already severe flow alterations. As water use is not balancing globally, a key component missing is the spatially explicit account of seasonal EFRs needed to safeguard the aquatic habitat. Even though not yet transgressed at global level, the global threshold would be lower when accounting for regional heterogeneity in natural flows (Gerten et al., 2013) and thus a regional Planetary Boundary based on EFR transgressions was proposed (Steffen et al., 2015). While it remains challenging to quantify the point at which regional water use has a globally destabilizing effect (i.e., the definition of a Planetary Boundary Zipper et al., 2020), non-sustainable water use, especially in view of SDG indicator 6.4 "sustainable withdrawals," needs to account for a more context-specific, bottom-up approach in which local ecosystem needs set boundaries for human water use. Local holistic methods for the comprehensive determination of EFRs are needed for effective implementations (Poff and Zimmerman, 2010). But simpler EFR representations in mechanistic global hydrological models (e.g., Smakhtin et al., 2004; Jägermeyr et al., 2017; Hanasaki et al., 2018; Rosa et al., 2018; Pastor et al., 2019) can already assist initial decision making. Such pilot estimates suggest that about 40% of irrigation water currently abstracted from surface water bodies is at the expense of environmental flows and needs to be reset (**Table 1**). In addition, roughly 20% of irrigation water use is depleting groundwater bodies (Döll et al., 2012; Wada et al., 2012b, 2016b), indicating that 50–60% of current global irrigation practice is unsustainable (Rosa et al., 2019). Most recently, EFR methods have been implemented in global gridded crop models, linking overdraft to food production (Jägermeyr et al., 2017; Rosa et al., 2018; Pastor et al., 2019; Gerten et al., 2020). While from a global food production perspective rigorously reallocating these water volumes to the ecosystem would only impinge upon about 5% of global caloric production (i.e., rainfed and irrigated production combined, Jägermeyr et al., 2017), in heavily irrigated systems such as Central and South Asia, current food production largely depends on unsustainable withdrawals (**Figure 2C**). A number of policy recommendations have been established to safeguard riverine ecosystems (e.g., Brisbane Declaration, 2007; Le Quesne et al., 2010; European Comission, 2015; FAO, 2019), but methodological, institutional, and financial challenges hinder broader implementation and recognizing nature as an equivalent water user (Smakhtin, 2008; Poff and Matthews, 2013).

2.2. Improving Crop Water Productivity

In general, there are two avenues to increase water productivity, either by reducing water losses or increasing the output per volume of water used. At global scale, irrigation systems operate at surprisingly low efficiency levels—only about a third of the diverted water is consumed by the crop—much is lost in the conveyance system or through inefficient application to the plant (Vickers, 2001; Molden, 2007; Jägermeyr et al., 2015, 2016). Although localized drip irrigation techniques can achieve efficiencies in excess of 95%, only 3% of irrigated land is operated under such systems worldwide (Postel, 1999; ICID, 2012; FAO, 2014a). Yet the mere focus on expansion of irrigated land has changed recently, and solutions increasingly focus on modernization of existing infrastructure (Faurès et al., 2007; Siebert et al., 2015). Substantial water productivity gains can be achieved through upgrades in irrigation systems at farm level (Postel, 1999; Molden, 2007; IAASTD, 2009; Molden et al., 2010; Al-Said et al., 2012; 2030 Water Resources Group, 2013; World Water Assessment Programme, 2015b). But scaling up irrigation efficiency improvements across water sheds has been hampered by misleading definitions of water "losses" and saving potentials, which still fuels an aged debate about the irrigation paradox: higher efficiencies can lead to increased consumption (Seckler, 1996; Perry et al., 2009; Frederiksen, 2011; Gleick et al., 2011; Christian-Smith et al., 2012; Jia, 2012; Jägermeyr et al., 2015; Grafton et al., 2018).

Two aspects are important to note herein: first, only part of the water diverted, but not beneficially used up by the crop (i.e., not transpired) can be considered a loss. A significant fraction (e.g., drainage, surface runoff) remains in the hydrological system and might be accessible downstream. Only irrigation water that is non-beneficially consumed (e.g., soil evaporation, evaporative conveyance losses, weed transpiration) might form accessible irrigation water losses, while reducing return flows can be desirable for other reasons. The traditional definition of irrigation efficiency (i.e., evapotranspiration by diverted water) disregards that evapotranspiration (i.e., soil evaporation plus plant transpiration) includes fractions accessible through better application and conveyance systems. Therefore, and because return flows are not accounted for, traditional irrigation efficiency approximates 100% at watershed level, which is misleading and merits revision. A beneficial irrigation efficiency measure has been proposed, that is, the ratio of beneficial (i.e., crop) transpiration and irrigation withdrawals (Jägermeyr et al., 2015), which partitions non-beneficial irrigation water fluxes and thus isolates losses even at watershed level.

Second, pursuits to increase irrigation efficiency do not necessarily translate into reduced water withdrawals, as farmers—in the absence of effective water regulation—generally rather expand irrigation or switch to higher value crops, instead of losing water allocations. Unchanged water diversion paired with more efficient systems results in reduced return flows into the river, which can have adverse effects for downstream users (Ward and Pulido-Velazquez, 2008; Grafton et al., 2018). Besides these valid arguments, any reduction in non-beneficial consumption through irrigation upgrades improves the overall crop water productivity at basin level. Irrigation improvements, however, do not directly increase crop yields, but water savings can be used to boost yields by expanding irrigation or toward reducing overdraft. But it is clear that policies and institutional legislation to regulate water reallocations become paramount to reset overdrafts already in place (Nelson et al., 2010; Simons et al., 2015).

The initially linear relationship between water application and yield levels off at high water inputs and many irrigated systems apply more water than needed (e.g., see Figure 5 in Molden et al., 2010; Lopez et al., 2017). Forms of deficit irrigation can thus reduce water requirements at marginal yields reductions, driving up water productivity substantially (Fereres and Soriano, 2007; Molden, 2007; Geerts and Raes, 2009; IAASTD, 2009; Lopez et al., 2017). Including application and conveyance losses, recent modeling studies confirm—in theory—that there are sizeable saving potentials in irrigated agriculture across regions worldwide. More than 40% of current irrigation water consumption might be accessible under ambitious irrigation transitions (**Table 1**) to either reduce use or expand irrigated areas (Brauman et al., 2013; Fishman et al., 2015; Jägermeyr et al., 2016; Lopez et al., 2017; Stenzel et al., 2019; Huang et al., 2020). However, dynamic quantitative water accounting and local net effects of irrigation transitions in account of non-trivial water trade-off dynamics along the river network are difficult to assess at global scale (Munia et al., 2016). Although global crop-hydrological models increasingly provide the infrastructure to represent mechanistic water partitioning, irrigation systems are still insufficiently represented in many models (e.g., Siebert and Döll, 2010; Elliott et al., 2014). In state-of-the-art global crop models contributing to the Global Gridded Crop Model Intercomparison project (GGCMI, Elliott et al., 2015; Franke et al., 2019; Jägermeyr et al., 2020), irrigation is assumed to be unconstrained by actual freshwater availability and to operate at loss-free water conveyance and application. In global hydrological models such as in the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP, Frieler et al., 2017) irrigation is usually constrained by surface and often also groundwater availability, but crops and different management forms are usually not explicitly represented (Wada et al., 2016a). In the next crop model intercomparison phase water-availability constraints and mechanistic irrigation processes need to be explicitly represented in multiple harmonized models, based on improved input data, to refine understanding of future water saving strategies, which can inform decision making and guide local feasibility assessments for implementation.

2.3. Rainfed Agriculture—The Crux of a New Green Revolution

The second avenue for increasing water productivity is increasing the yield output per water used. Important in irrigated systems as well, but especially in rainfed agriculture it includes agronomic practices such as water harvesting, supplemental irrigation, and soil and water conservation. The contribution of irrigation to global food security has been tremendous and will even increase in the future (Faurès et al., 2007; World Water Assessment Programme, 2015b), but irrigation alone will not be sufficient to attain the SDG food targets (Rockström et al., 2007b; Davis et al., 2017; Keys and Falkenmark, 2018). New substantial freshwater allocations are required to bring current food production on a par with future demands: 5,200 km^3/yr of additional blue and green water might be needed by 2050 under current water productivity levels (SEI, 2005; Rockström et al., 2007b). However, such volumes have to originate to 85% from green water on current rainfed land, that is, through maximizing water productivity, as arable land is scarce and irrigation expansion limited (SEI, 2005; Schyns et al., 2019). The majority of food production at global level—currently about 60%—remains rainfed for the foreseeable future (Siebert and Döll, 2010; FAO, 2011; Keys and Falkenmark, 2018).

The first Green Revolution focussed on areas with sufficient precipitation or irrigation, where returns were high (Pingali, 2012). Tackling today's yield gaps requires more marginal regions to come into focus, with water constraints in semi-arid and mostly rainfed regions. In these drought-prone and low-yielding systems, the lack of water is of principal concern, because it subsists a co-limitation of nutrients and water. Replenishing soil fertility will often not have much effect, until sufficient soil moisture becomes available to the plant (Oweis and Hachum, 2006). Yet, an important aspect is that it is often not about the total amount of precipitation per year that imposes greatest problems, but unreliable and erratic rainfall (i.e., dry spells and periodic water scarcity) (Wani et al., 2009). In addition, poor farm water management characterized by excessive on-farm water losses in semiarid tropical systems provokes root zone drought and resulting low yields (1-2 t/ha) (Oweis and Hachum, 2006; Rockström et al., 2007b). On average, a large fraction of available precipitation (and irrigation) water runs off unused, evaporates non-beneficially from bare soils, or percolates below the plant root zone. Such losses of non-beneficial green water flows lead to a nonlinear relationship between yield growth and water consumption, which indicates a particularly great opportunity to improve water productivity at the low-yield range in savanna agro-ecosystems (Rockström et al., 2003). A doubling of staple crop yields in many parts of sub-Saharan Africa seems indeed achievable with current know-how, through relatively small manipulations of rainwater partitioning (Rockström and Falkenmark, 2000; Molden, 2007; Pretty et al., 2011; Jägermeyr et al., 2016). In fact, this is the world's largest untapped potential to safe water in food production (Falkenmark et al., 2009).

Climate change with altered rainfall patterns might impose additional stress on agricultural systems, both rainfed and irrigated, but particularly for smallholders in semi-arid regions (Falkenmark et al., 2009; Porter et al., 2014). Field studies, however, demonstrate a wide spectrum of long-known agro-ecological practices to increase plant water availability and thereby climate resilience through e.g., maximizing soil infiltration, collecting surface runoff for supplemental irrigation, and alleviating soil evaporation (e.g., Fox and Rockström, 2003; Welderufael et al., 2008; Araya and Stroosnijder, 2010). Improved crop varieties and rotations adapted to dryland farming, optimum crop geometry, agroforestry, and conservation tillage can also play an important role in increasing plant water uptake and thus stabilizing yields (Duivenboodew et al., 2000; Rockström et al., 2007a). Such readily available measures are being implemented sporadically around the world, leaving huge untapped potential to scale up (Mati et al., 2007; Barron et al., 2015; Searchinger et al., 2018). Rockström and Karlberg (2010) therefore call for a "triple Green Revolution": intensify food production; within environmental limits; and mainly focused on green water. These facts render remarkable hydro-climatic opportunities for on-field water management interventions in rainfed farming to improve yield levels, smallholder climate resilience, and—most importantly—livelihoods of the poor (Biazin et al., 2012).

2.4. Water Management as a Pivot Toward Closing the Future Food Gap

Today the debate about sustainable intensification of agriculture (The Royal Society, 2009; Foley et al., 2011; Foresight, 2011; Tilman et al., 2011; Garnett et al., 2013; Gunton et al., 2016; Hunter et al., 2017; Rockström et al., 2017; Pretty, 2018; Pretty et al., 2018) goes past the two-dimensional clash of "growth without limits" or "limits to growth." Envisioning a sustainable future, the focus shifted toward growth within limits or "abundance within Planetary Boundaries" (Rockström and Klum, 2015). This middle ground now forms the nexus in which to move beyond a focus on biophysical limits only and toward solution-oriented research, developing pathways to exploit "planetary opportunities" (De Fries et al., 2012).

In the historical context, it is clear that a third agricultural upswing is imperative—the sustainability revolution. There are repeated calls for a second Green Revolution (e.g., Conway, 1999; Annan, 2003; Ki-moon, 2008), now with the recognition of environmentally sound strategies. Previous research, cited above, has shown that there are sizeable management opportunities in both irrigated and rainfed systems worldwide. Combined, ambitious water management strategies across scales can significantly increase global food production while relieving pressure on freshwater resources (e.g., Gerten et al., 2020). Here updated simulations, based on model configurations in previous publications (Jägermeyr et al., 2016, 2017; Gerten et al., 2020, see **Appendix**), highlight that such measures can over-compensate losses associated with rigorously safeguarding EFRs and further increase global caloric food production by 30% compared to the current situation (**Figure 2C**). Independent approaches arrive at similar estimates (Rost et al., 2009; Brauman et al., 2013; D. Chukalla et al., 2015; Huang et al., 2020).

Yet, food demand is expected to increase by 60–100% a few decades into the future. Closing the future food gap sustainably requires bringing together additional measures (Grafton et al., 2017; Kummu et al., 2017). Solutions must integrate strategies harnessing opportunities in all domains of the food system, capitalizing on synergies and co-benefits, embedded in landscape approaches. These measures include yield gap closures not just through improved water supply, but soil fertility management and crop rotation, precision agriculture with targeted fertilizer application and integrated pest management, genetic improvement of crop's stress resistance and nutrient efficiency, reduce food losses (Jalava et al., 2016; Ritchie et al., 2018), and importantly, change human diets toward lower animal protein intake (Springmann et al., 2018; Willett et al., 2019). Naturally, efforts to advance toward replacement level fertility would help reduce future food demand, especially if in synergy with attaining other SDGs (e.g., Abel et al., 2016). Linking supply and demand, food trade is a critical element of any solution to global food security, underlined by the fact that today 80% of people live in net food-importing countries (Porkka et al., 2013; MacDonald et al., 2015).

Recently, evidence accumulates showing that the safe and just space in terms of food production within planetary boundaries indeed exists. Modeling studies suggest that attaining sustainable future food security in recognition of the planetary boundaries would be narrowly possible (Conijn et al., 2018; O'Neill et al., 2018; Springmann et al., 2018; Gerten et al., 2020). However, these results build on a progressive transformation of current agricultural systems. Fertilizer application need to be redistributed, land use pattern revised, water use regulated, and biodiversity maximized (e.g., Pretty et al., 2018).

It is clear that water management is not a panacea and will not be sufficient to attain the 2030 Agenda in isolation. It is considered a critical starting point for sustainable intensification and it integrates into more holistic agro-ecological landscape approaches to further maximize synergies and to adapt to local requirements (see e.g., Tittonell et al., 2012; Marques et al., 2016). While the implementation of water targets face financial, institutional, and cultural challenges, returns include important co-benefits, especially in the developing world. Improved irrigation systems can improve crop quality, reduce application of fertilizer and pesticides and thus improve water quality, and reduce water logging (Gleick et al., 2011; Calderón et al., 2014). Localized irrigation, water harvesting, mulching, and conservation tillage can reduce soil degradation, and help control weeds (Liniger et al., 2011), which is essential for integration into larger landscape conservation approaches (e.g., Duivenboodew et al., 2000; Marques et al., 2016). Degraded soils (i.e., soil erosion and loss of soil organic matter and nutrients) currently affect >60% of the cropland in sub-Saharan Africa (Liniger et al., 2011). Its restoration is an important prerequisite for sustainable intensification; a positive example at scale is the Great Green Wall Initiative spanning across the Sahel (African Union and UN Convention to Combat Desertification, 2020). Conservation agriculture in general will also help mitigate greenhouse gas emissions (Mahdi et al., 2015). As probably the single most important synergy, water management intervention can expand economic opportunities, and is often a prerequisite for smallholders to invest in higher inputs such as fertilizer or irrigation (Conway, 1999; Biazin et al., 2012; Burney et al., 2013). Low-cost measures including organic mulching, conservation tillage, and simple drip kits, can catalyze a shift past low input-output systems and directly translate into improved livelihoods (Postel et al., 2001; Kahinda and Taigbenu, 2011). Upfront investment needs can be steep, but long-term economic analyses confirmed the substantial net profits achievable (Fox et al., 2005; Biazin et al., 2012). Given that many poor subsist on water-constrained agriculture, the associated scope for poverty alleviation and improved local food security is tremendous (Dillon, 2011; Burney and Naylor, 2012; World Water Assessment Programme, 2015b).

Infrastructure development for small-scale water harvesting systems are associated with investments comparable with those for basic sanitation and water supply (Rockström and Falkenmark, 2015). Off-the-cuff calculations for irrigation transitions costs, assuming upper-end per hectare investments for drip irrigation of US$ 1,000–18,000, come down to 100–1,800 billion for 100 Mha crop land—a third of irrigated area worldwide. When weighing these large upfront capital costs, it is important to account for the costs of not taking action. Degrading ecosystems can be of substantial value (Poff et al., 2015), Costanza et al. (2014) estimate that US$ 3,000–10,000 billion per year worth of ecosystem services were lost due to disappearing wetlands.

Water governance is needed to allocate water resources to high-value uses and to balance priorities amongst competing demands (Falkenmark et al., 2007; Hoekstra, 2011; World Water Assessment Programme, 2015b). For instance, most economic models are yet to value the services provided by freshwater ecosystems. There are positive examples, e.g., in the USA (Kendy et al., 2012) or China (Zhang et al., 2012), but water management practices are often fragmented, leading to lost synergies, poor trade-offs, and are not readily transferable (Boelee, 2011). Even though central to sustainable intensification of agriculture, these farm water management strategies are currently insufficiently represented among international development policies (Rockström and Falkenmark, 2015; Searchinger et al., 2018).

The main principles for sustainable intensification of agriculture are evident: (i) improve efficiency in resource use; (ii) expand or redistribute inputs to underperforming systems, and (iii) conserve and enhance natural ecosystems (e.g., FAO, 2014b). However, there is a clear research gap regarding how to implement these goals at scale. Many promising ideas and local solutions prove successful (e.g., Pretty et al., 2006, 2011; Cui et al., 2018; Pretty, 2018; Searchinger et al., 2018)—by 2018 about 163 million farms use at least one component of conservation agriculture (Pretty, 2018; Pretty et al., 2018). But knowledge of how to transform agricultural systems across scales, in respect of various limiting biophysical, institutional, economic, and cultural factors is largely missing. Despite the prominent position in the 2030 Agenda, the global potential of sustainable intensification of agriculture, and especially the water dimension therein, is widely unknown.

In view of the broader historical human race for food, new innovations will certainly create technological fixes, which will further push the envelope of opportunities. But when faced with the scale of untapped potentials associated with traditional practices, the next agricultural pivot appears to be, above all, an implementation challenge.

AUTHOR CONTRIBUTIONS

JJ performed the LPJmL simulations, analyzed the data, prepared the figures, and wrote the manuscript.

FUNDING

JJ received support from the Leibniz Competition (SAW-2013-PIK-5) and the Open Philanthropy Project, and partly from the U. Chicago RDCEP center (NSF grant #SES-146364).

ACKNOWLEDGMENTS

I thank Yoshihide Wada for providing groundwater depletion data and Dieter Gerten and Wolfgang Lucht for valuable comments on an early manuscript version. Part of the material presented here first appeared in my thesis, which can be accessed online (Jägermeyr, 2017).

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Conflict of Interest: The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

APPENDIX

Global simulations of irrigation water use, environmental flow requirements, and EFR transgressions as shown in **Figure 1B** are performed with the global agro-hydrological model LPJmL. Model configurations and input data setups are as in Jägermeyr et al. (2017). The only difference is the consideration of a transient land-use input (Siebert et al., 2015) to account for historical changes over the 20th century. Simulated water use and EFR transgressions shown in **Figure 1B** are based on the average of three different historical re-analysis weather data inputs and three different EFR calculation methods (see Jägermeyr et al., 2017 for more details).

Farm water management potentials are also simulated with the LPJmL model, based on assumptions in Jägermeyr et al. (2016). The "ambitious water management" scenario presented here refers to water and soil management interventions in both irrigated and rainfed systems. It includes best-practice irrigation upgrades, that is, switching to drip irrigation where possible and sprinkler systems otherwise, only paddy rice is assumed to operate under surface irrigation. Irrigated areas are assumed to expand based on water saved through efficiency improvements. Rainfed systems are simulated under supplemental irrigation through rainwater harvesting and partial alleviation of soil evaporation through mulching and conservation tillage. These management practices are based on assumptions in Jägermeyr et al. (2016). New simulations are performed here to combine the effects of maintaining EFRs with the "ambitious water management" scenario in Jägermeyr et al. (2016). Jägermeyr et al. (2017) also includes farm water management scenarios, but not the more ambitious one use here. Farm water management potentials are simulated under constant land use pattern representing the year 2005, and all other model setups and configurations are as in Jägermeyr et al. (2016) and Jägermeyr et al. (2017).