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More food, but less land and water for nature: Why agricultural productivity gains did not materialize

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ABSTRACT

Realism about productivity gains in agriculture and water is critical to understand if the world can feed itself while protecting nature. We use government-reported data to review progress over 2000–2020 compared to projections for irrigated and rainfed agriculture and trade. Our results over the period 2000–2020 show that productivity gains largely did not materialize. Instead of consolidating cereal production and trade in favourable regions like North America, Europe and Russia, their arable land declined by 35 million hectares, while arable land expanded by 74 million hectares in Africa, Latin America and Eastern Asia. Likewise, water productivity gains did not materialize, as photosynthesis breakthroughs did not occur. Land productivity (yield) gains were projected to rise 21–61 %, making the observed increase in cereal yields of 31 % a slight one. This puts the world on the path of using steadily more land and water to produce food and feed, at the expense of nature. Solutions to veer off this path include reducing food demand (including dietary change), stabilising rainfed agriculture and broadening the crop genetic resources base.

1. Introduction

This paper advances a realistic understanding of the potential for productivity gains in land and water by exploring actual progress in trade and agriculture in the past 20 years and proposing alternative ways forward. Food production objectives have gained added urgency with continued population growth, food insecurity, and malnutrition, but also forefront is the need to limit agricultural water use, loss of biodiversity, deforestation, water shortages, and climate change (Reid et al., 2019; FAO et al., 2023; IPCC, 2023). Balancing these imperatives is challenging, because the physical connections between crops and water limit potential for optimization. Photosynthesis efficiency has hardly improved in past decades (Sinclair et al., 2019; Araus et al., 2021), and yield gains for major food cereals are slowing (Lampietti et al., 2011; Rizzo et al., 2022). Agronomists know this, but this insight is often overlooked in the broader water and food research community, where scenario studies portray large potential to further optimize global trade and increase productivity in rainfed and irrigated agriculture (Postel, 1998; Rockström et al., 1999; Gerten et al., 2020; Bayer et al., 2023). This generates the misperception that water and food production can be readily optimized for food security and environmental protection.

To advance a realistic understanding, we compared developments in trade and rainfed and irrigated agriculture during 2000–2020 with projections from a large scientific collaboration on water management in agriculture. The Comprehensive Assessment of Water Management in Agriculture (henceforth ‘Comprehensive Assessment’), led by the CGIAR global research partnership for food security, involved over 700 scientists in the early 2000s and was published in 2007 (Molden, 2007). The study formulated six scenarios, including trade and optimistic and pessimistic assumptions in crop evapotranspiration and harvested area for rainfed and irrigated agriculture. The scenarios concern regional yields of wheat, rice and maize, as these crops supply half of the world’s food-caloric intake.

But why is there limited potential for optimization? Growing more food with less water hinges on productivity improvements in land (more

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tonnes per hectare) and water (more tonnes per m3 crop water evapotranspiration). During and after the Green Revolution, gains in land productivity (defined in this study as yield in tonne per hectare) were achieved by breeding, fertilizer and the introduction of irrigation. Improvements in harvest index at first were substantial, as yields rose with relatively less water transpired. More recently, however, yield gains have slowed for major cereal crops, indicating there may not be much potential left (Peng et al., 1999; Lo Valvo et al., 2018; Rizzo et al., 2022). In addition, interventions to increase land productivity (e.g., increased planting densities or shorter growing seasons that allow for an extra crop) tend to come with increases in annual crop evapotranspiration as biomass and crop evapotranspiration are linearly related (De Wit, 1958; Steduto et al., 2007).

Photosynthesis is the major determinant of crop water productivity (smaller influences stem from optimal nutrients, variations in local climate and reductions in non-beneficial evaporation (Steduto et al., 2007). Crop water productivity is defined as ratio between biomass produced and water consumed through evapotranspiration (Steduto et al., 2007). Photosynthesis dictates how efficiently a crop converts water into biomass. Hence, improving photosynthesis efficiency, defined as the ratio by which a crop captures light and converts it into biomass over the growing season (Simkin et al., 2019), is key to form more biomass with the same amount of water transpired. Reviews conclude, however, that for nearly 30 years increases in photosynthesis have been very marginal at crop level (Sinclair et al., 2019). While a meta-review of crop water productivity studies (Zwart and Bastiaanssen, 2004) found a large range of water productivity estimates, and thus apparent scope for higher crop water productivity, the quality of the included studies raises concern. Only 21 % of the studies could be verified (see SI Appendix). Thus, the range in reported crop water productivity might be explained by questionable procedures rather than true variation.

Studies using satellite imagery and irrigation efficiency further overestimate the potential to optimize water. Remote sensing data on water productivity contains seeming variation in biomass and evapotranspiration, whereas analysis of statistical trends confirms the steady value of water productivity, as biomass and evapotranspiration is controlled by a nearly stable photosynthesis efficiency (Seijger et al., 2023). Lastly, gains in irrigation efficiency, defined as ratio between volume of irrigation water beneficially used and total volume of irrigation water applied (Grafton et al., 2018), are often incorrectly equated with water savings. In practice, they rarely reduce water consumption (Grafton et al., 2018). Saved water is frequently reallocated by farmers to intensify production, resulting in higher crop water evapotranspiration at basin scale (Perry, 2007; Van Halsema and Vincent, 2012). This understanding of the irrigation paradox, ‘more efficient irrigation systems deplete more water’, is questioned through detailed water accounts and modelled conversions of non-beneficial consumption and non-recovered flows to beneficial consumption for agriculture (Lankford, 2023). Such water accounts also indicate how conserved agricultural water could be redistributed to nature or society (Lankford and Scott, 2023).

In sum, different schools of thought exist regarding the gains to be achieved in land productivity and water productivity (Molden et al., 2007), ranging from scepticism (e.g. Sinclair et al., 1984; Rizzo et al., 2022) to modest optimism (e.g. Bayer et al., 2023; Van Opstal et al., 2021). Yet the optimism of keeping agriculture and crop production within sustainable limits through productivity gains in rainfed and irrigated agriculture is poorly supported by agronomic and empirical water resources research. To come to a more realistic understanding, this paper explores progress in agriculture and trade over 20 years, compared to projections in the Comprehensive Assessment. The analysis focused on arable land for temporary crops; area equipped for irrigation; and production and trade data for maize, rice and wheat. The years compared were 2000 and 2020, using five-year averages to smoothen year-to-year fluctuations and extreme years using data from FAOSTAT (FAO, 2023). For 2000, the 1996–2000 average was used. For 2020, the average of 2016–2020 was taken. The FAOSTAT database provides a clear indication of the extent that productivity gains materialized on farm fields around the globe, as nearly all countries report their production data to FAO, and the data is online and readily available. The analysed data is shared in the Supplemental file (SI Appendix). Our method is detailed at the end of the manuscript.

2. Method

To compare the Comprehensive Assessment scenarios with reported regional trends for 2000–2020 we followed three steps. First, we sought variables from the Comprehensive Assessment scenarios that could be verified in online global databases. This resulted in the selection of three variables: yield, area and net trade. Comprehensive Assessment yield projections for rice, wheat and maize were obtained for the pessimistic and optimistic rainfed and irrigation scenarios (Table 3.5 and 3.9 in Molden, 2007). Projected area changes in production regions were derived for irrigated and rainfed areas from the optimal scenario (Table 3.13 in Molden, 2007). Net cereal trade flows (exports minus imports) were extracted for the rainfed (pessimistic and optimistic), irrigation (pessimistic and optimistic), trade and optimal scenarios (Table 3.11 and 3.13 in Molden, 2007). For crop evapotranspiration, we were limited to the use of the global water use figures presented in the Comprehensive Assessment, due to the absence of trustworthy global data on crop evapotranspiration. Crop evapotranspiration is difficult to measure at regional to global scales. Local point measurements are not representative of larger regions, and large-scale remote sensing relies on multiple coarse data inputs to calculate evapotranspiration.

Second, we extracted country data from FAOSTAT in March 2022. FAOSTAT data was used as nearly all countries annually report agricultural production and trade figures to FAO through their agricultural ministries. Over- and underestimations do occur in this self-reported data (Carletto et al., 2015). However, the transparency of the data likely helps to uphold accuracy, as FAOSTAT data is online and freely accessible. Land data was obtained through ‘arable land’, which is land used for cultivation of temporary crops in rotation with fallow and meadows, and ‘land area equipped for irrigation’, which is land with irrigation equipment in working order to provide water to crops. Rainfed area was calculated by subtracting arable land minus land equipped for irrigation. This probably resulted in an optimistic estimate of rainfed areas, as small-scale irrigation, supplemental, farmer-led and informal irrigation systems are generally counted as rainfed (Woodhouse et al., 2017).

Yields were calculated by dividing crop production by crop area for rice, wheat and maize. Separation of rainfed and irrigated yields was not feasible because FAOSTAT does not provide rainfed yields. GAEZ, a database with rainfed country yields, was discarded, as cereal rainfed yields were greater than 15 tonne/ha in eastern Africa. Net cereal trade was calculated per country as exports of cereal (rice, wheat and maize) minus cereal imports. The total net trade value at the production region level is the sum of net trade in all countries. Intraregional trade is thus not separately addressed. Intraregional trade is a smaller (Wellesley et al., 2017) and a less interesting strategy for reducing agricultural water use than interregional trade. Intraregional food trade within a river basin, for instance, does not necessarily reduce total water consumption in that basin. Although intraregional food trade may be important in some regions, differences in water abundance, rainfall availability and productivity are larger between regions than within regions, due to greater differences in climate.

Third, a regional analysis was done in which FAOSTAT data was compared to the Comprehensive Assessment scenario projections. To smoothen yearly fluctuations and extreme years in the country data, five-year averages were calculated for 2000 (average of 1996–2000) and 2020 (average of 2016–2020). FAOSTAT data was aggregated into the seven regions used in the Comprehensive Assessment. The

Comprehensive Assessment adopts the FAO grouping common in 2002: sub-Saharan Africa, Latin America and the Caribbean, the Near East and North Africa, South Asia, East Asia, the OECD[1], and Eastern Europe and Central Asia. Trends in trade, yield and area were then compared graphically to the 2050 projections of the Comprehensive Assessment scenarios. Specifically, our comparative analyses assessed whether actual trends were in line with the Comprehensive Assessment scenarios or whether trends had moved in entirely different directions. All data used in the analysis is available in the supplemental file (SI Excel file).

3. Results

3.1. Trends 2000–2020, five-year averages

Fig. 1 shows trends in arable land use for cultivation of temporary crops in rotation with uncropped land (e.g., fallow, meadows and pasture). Rotation happens due to soil health and unfavourable growing conditions (e.g., too cold or insufficient rainfall).

Total arable land for cultivation of temporary crops increased marginally over the study period, from 1361 million hectares in 2000 to 1387 million hectares in 2020. The area equipped for irrigation increased from 280 million hectares to 342 million hectares. The rainfed area under temporary crops dropped from 1081 million hectares to 1045 million hectares. The area under permanent crops (e.g., fruit trees, palm trees, coffee, oil palm trees and rubber) increased by 48 million hectares, from 129 million hectares to 177 million hectares. The area of permanent crops is not shown in the figure, as the Comprehensive Assessment focused on cereals due to their role in meeting food and feed demands. Regionally, Fig. 1 shows strong decreases in arable land in the OECD and Central Asia, whereas strong increases are found in Latin America, sub-Saharan Africa and Eastern Asia. The Middle East and North Africa (MENA) region and South Asia show a small decline. The division between rainfed and irrigated land is rather stable, with the largest increases in irrigation in East Asia, South Asia and MENA.

Global average yields of key cereal crops increased in the range of 19–33 %. Maize yields increased from 4.3 to 5.8 tonne/ha, rice from 3.8 to 4.6 tonne/ha, and wheat from 2.7 to 3.5 tonne/ha. Aggregate cereal yield rose 31 %, from 3.5 tonne/ha to 4.6 tonne/ha. Total export of these cereals increased by 91 %, from 188 million tonnes in 2000 to 359 million tonnes in 2020. Production and export over this period somewhat improved food security. While the global population grew by more than 1.5 billion people, the prevalence of malnutrition dropped at the global level over 2005–2020, though the number of undernourished people in Africa and West Asia increased after 2017 (FAO et al., 2023).

The Comprehensive Assessment presents yield projections for cereals in the range of 21 % (pessimistic) to 61 % (optimistic). The observed 31 % yield increase in rice, wheat and maize is thus slightly higher than expected under the pessimistic growth assumptions. In addition, the total arable land under temporary crops, which was 1387 million hectares in 2020, had already surpassed the projection for 2050 in the optimal scenario. This puts the optimistic rainfed and irrigated scenarios well out of reach, as actual developments reflect a much more pessimistic trend of agriculture requiring more land and water to meet food demand. Less land and water is therefore available for the natural environment, aggravating ecological degradation. This is in line with the worldwide conversion of forests and savannahs into cropland (Winkler et al., 2021), the decline in freshwater volumes in lakes and rivers (Yao et al., 2023) and rapid and accelerating decline of groundwater-levels in aquifers, especially in dry regions with extensive croplands (Jasechko et al., 2024).

3.2. Global trade

The Comprehensive Assessment points to global trade as the most promising option to reduce future growth of land and water use in agriculture. This assumes that food moves freely over the globe through trade. Food can thus be produced in regions and countries where land and water are relatively abundant, to be traded with countries with a demand for food but a lack of abundant resources to produce it. This strategy is particularly attractive for global optimization of cereal production, as cereals have high caloric value and low economic value, making their import relatively affordable. Favourable cereals production regions, due to climate, land and water conditions (e.g., Central Asia and Eastern Europe, Latin America, and OECD countries), can thus produce surpluses to feed unfavourable regions through trade (e.g., MENA, Southern Asia and East Asia).

Yet, our assessment shows that in two of the three key favourable regions, cereal exports (maize, wheat and rice) plummeted rather than increased towards 2020 (Fig. 2). In OECD countries, the decline in cereal trade is explained by a 7 % drop in rainfed production area (Fig. 3) and by the widespread use of maize as a biofuel feedstock in the United States (Erenstein et al., 2022). In Latin America, rainfed area increased, but to grow soy rather than cereals (Mekonnen et al., 2015). Similarly, Central Asia and Eastern Europe are considered favourable regions. Yet, despite their increasing cereal exports since 2000 (Fig. 2), rainfed and irrigated areas here, too, are shrinking (Fig. 3), directly reducing surpluses for export. Agricultural land has also declined in Russia and the post-Soviet regions, reflecting the continuation of a trend since the collapse of the Soviet Union (Naumova et al., 2020). Developments in all three key cereal production regions are a major setback for optimizing global food production with minimum impact on water and nature.

The decline in rainfed cereal production area and trade likely corresponds to two processes. The first is climate change, which is bringing more frequent and extended shocks to rainfed cereal production (Lesk et al., 2016). The second is falling profit margins in cereal farming, due to low farmgate prices, high input costs and stricter environmental regulations (Giller et al., 2021). The compound effect of higher climate risks and lower margins increasingly drives cereal farmers out of business (Dubman et al., 2021) or (when possible) causes them to shift to higher value crops, particularly in Latin America, South Asia and China (Giller et al., 2021).

A final factor undermining the trade strategy is volatilities in global trade. The global food market reeled from price hikes and volatilities in 2008, 2011, and in 2022 with the onset of the war in Ukraine. Price hikes have acted as disruptors of the global trade strategy – as prices spiked, food insecurity and poverty increased, especially in cereal-importing regions (Lin et al., 2023). As trade failed, governments were quick to (re)prioritize national food security, by limiting exports (Luckmann et al., 2015), expanding national production (Christoforidou et al., 2023) and grabbing land and water abroad to meet domestic demand (Rulli et al., 2013). The strong area reductions in favourable cereal production regions over the period 2000–2020 also signal that the global trade strategy is out of reach.

3.3. Rainfed agriculture

The rainfed strategy is the Comprehensive Assessment's second most effective option for raising agricultural output with minimal increase in water and agricultural land use. Rainfed agriculture would then supply nearly all of the additional food demand in 2050, mainly thanks to strong yield increases with limited area expansion. Appropriate and extensive use of high-yielding varieties, improved soil fertility and good agronomic practices would unlock this potential, doubling or nearly tripling agricultural output per rainfed area.

Our assessment, however, shows that little progress was made in this regard over the period 2000–2020. Not only are key rainfed production areas shrinking in size (in the OECD, Latin America, Central Asia and

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[1] Organisation for Economic Cooperation and Development, an intergovernmental organisation with 38 member countries (see map Fig. 1 for an overview).

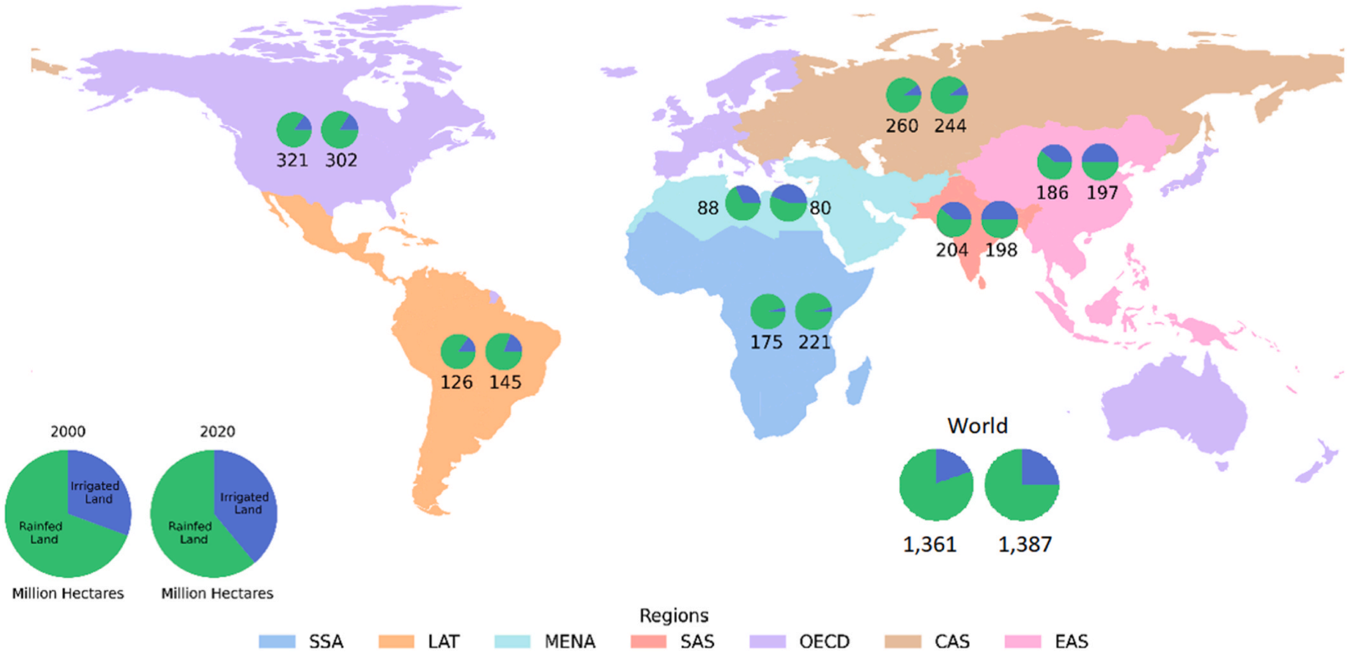

Fig. 1. Total arable land under temporary crops (million hectares), land share equipped for irrigation (blue), and land share under rainfed agriculture (green) in 2000 (1996–2000 average) and 2020 (2016–2020 average). SSA is sub-Saharan Africa, LAT is Latin America, MENA is Middle East and North Africa, SAS is Southern Asia, OECD is OECD countries, CAS is Central Asia and Eastern Europe, EAS is Eastern Asia. Data source: FAOSTAT data on ‘Arable land’ and ‘Land area equipped for irrigation’.

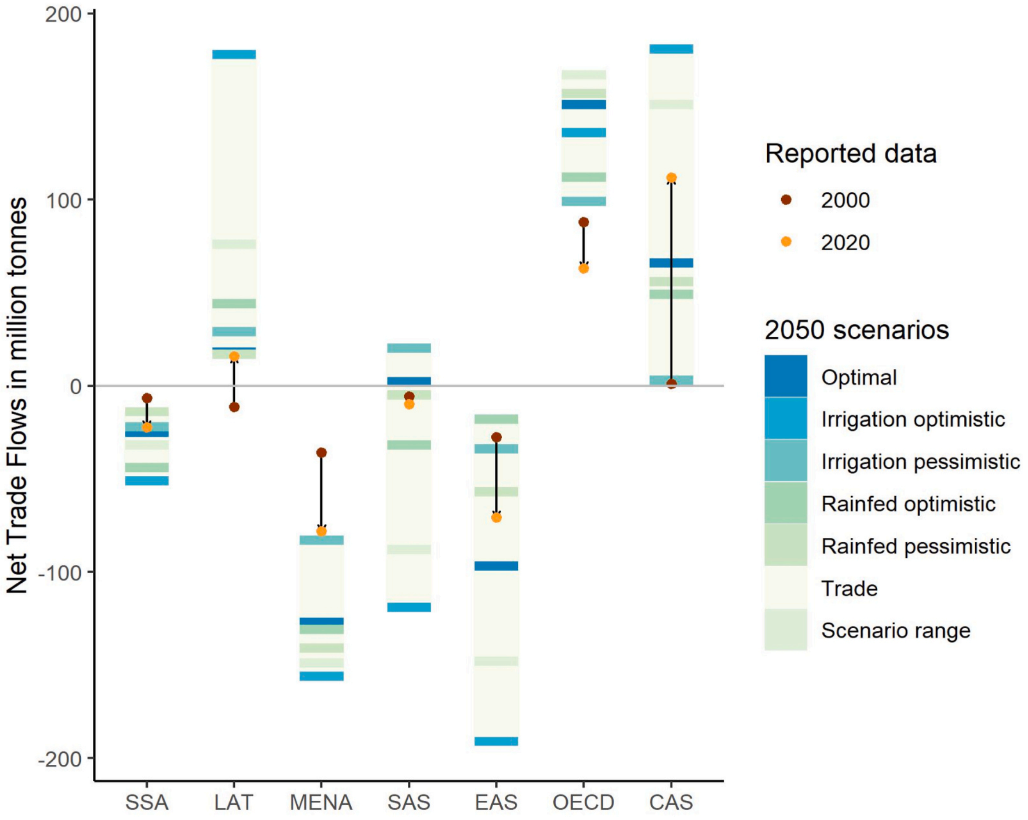

Fig. 2. Regional net cereal trade of wheat, rice and maize in 2000 and 2020 (reported data FAOSTAT) and in 2050 (projections). Positive values are exports, negative values are imports. SSA is sub-Saharan Africa, LAT is Latin America, MENA is Middle East and North Africa, SAS is Southern Asia, EAS is Eastern Asia, OECD is OECD countries, CAS is Central Asia and Eastern Europe. Data sources: FAOSTAT data on ‘Export Quantity’ and ‘Import Quantity’ for rice, wheat and maize; Comprehensive Assessment for net cereal trade flows 2050.

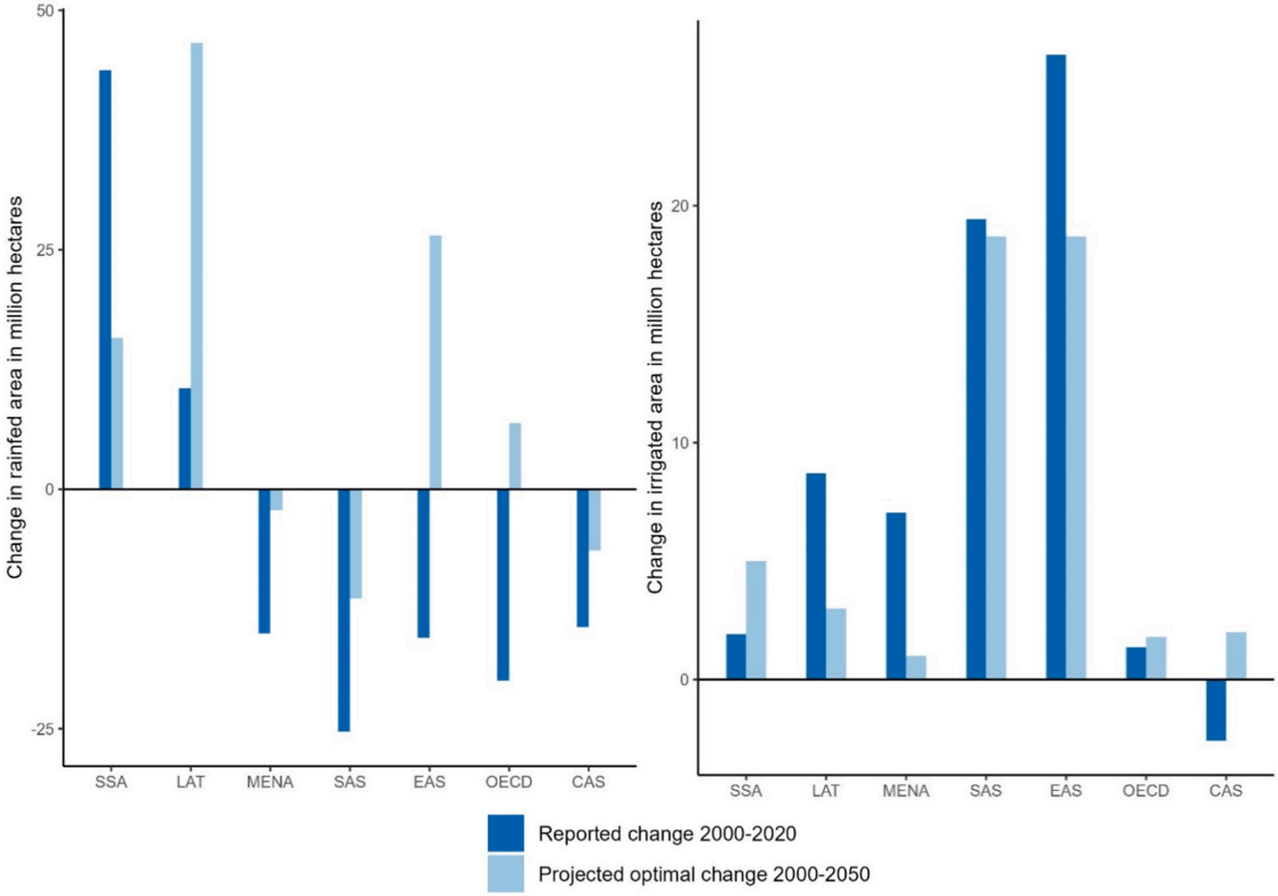

Fig. 3. Area change in rainfed (left) and irrigated agriculture (bright) from 2000 to 2020 (reported data) and from 2000 to 2050 (projected, optimal scenario). SSA is sub-Saharan Africa, LAT is Latin America, MENA is Middle East and North Africa, SAS is Southern Asia, EAS is Eastern Asia, OECD is OECD countries, CAS is Central Asia and Eastern Europe. Data source: FAOSTAT data on 'Arable land' and 'Land area equipped for irrigation'; Comprehensive Assessment optimal scenario for changes in rainfed and irrigated land 2000–2050.

Eastern Europe), but yields in the predominantly rainfed sub-Saharan Africa have hardly improved (Fig. 4). Sub-Saharan Africa's increase in cereal production has instead come from a massive expansion in rainfed area (Fig. 3), with yields remaining low (Fig. 4). This expansion is rightly described as massive, as by 2020 rainfed area in sub-Saharan Africa had already grown to twice the size projected for 2050 in the optimal scenario of the Comprehensive Assessment. However, this fast expansion of rainfed agriculture in this region means there is less land and water available for the natural environment.

Apparently, expanding rainfed agricultural land is a lot easier than improving yields and agronomic practices – not withstanding copious science and good intentions. Similar to the OECD, prevailing socio-economic risks and constraints may explain the lack of productivity gains in rainfed sub-Saharan Africa. Accelerating climate change, bringing temperature shocks and rainfall deficits, is increasingly affecting rainfed production (Funk and Brown, 2009), while the high and still rising cost of chemical fertilizers (Brunelle et al., 2015) has grave implications for the profitability of fertilizer use (Jama et al., 2017). Farmers thus seem to be expanding agricultural area with low fertilizer input, for very low cost production, as a means to cope with the higher risks. In conclusion, the land productivity and water productivity gains foreseen in the rainfed strategy have by and large failed to materialize. Area expansion in rainfed agriculture has not gone as anticipated. Globally, rainfed area diminished, and the unexpectedly large area expansion in sub-Saharan Africa has remained impeded by low yields.

3.4. *Irrigated agriculture*

In the Comprehensive Assessment, the irrigation strategy foresees a modest expansion in irrigated area and a strong increase in irrigated cereal yields. Irrigation was expected to make a relatively small contribution to the doubling of agricultural output by 2050, because irrigated area is much smaller than rainfed area.

Our assessment, however, shows that irrigation expansion has been quicker and more extensive than predicted in the optimal Comprehensive Assessment scenario. In Asia, Latin America and MENA, the reported growth in irrigated land in 2020 had already surpassed the projections for 2050 (Fig. 3). Irrigation expansion thus appears to be a main vehicle for increased production, mostly by converting lower yielding rainfed areas into higher yielding irrigated areas. As a result of this conversion, rice and wheat yields rose in Eastern and Southern Asia (Fig. 4). Significant additional contributions from irrigated agriculture to global food supply in 2030–2050 are expected to come from rainfed areas that (still) have abundant water resources but are converted into irrigated lands in the coming decades. These, however, will also face increasing water shortages, a point also made by Rosa et al. (2020). South America, Northwest Europe and China are also expected to contribute to a rise in irrigated output due to areas newly equipped for irrigation.

Greater land and water use for irrigated agriculture, however, comes at the direct expense of nature and other competing uses. Current estimates suggest that 40–50 % of all water consumption in irrigated agriculture is unsustainable (Jägermeyr et al., 2017; Rosa et al., 2019;

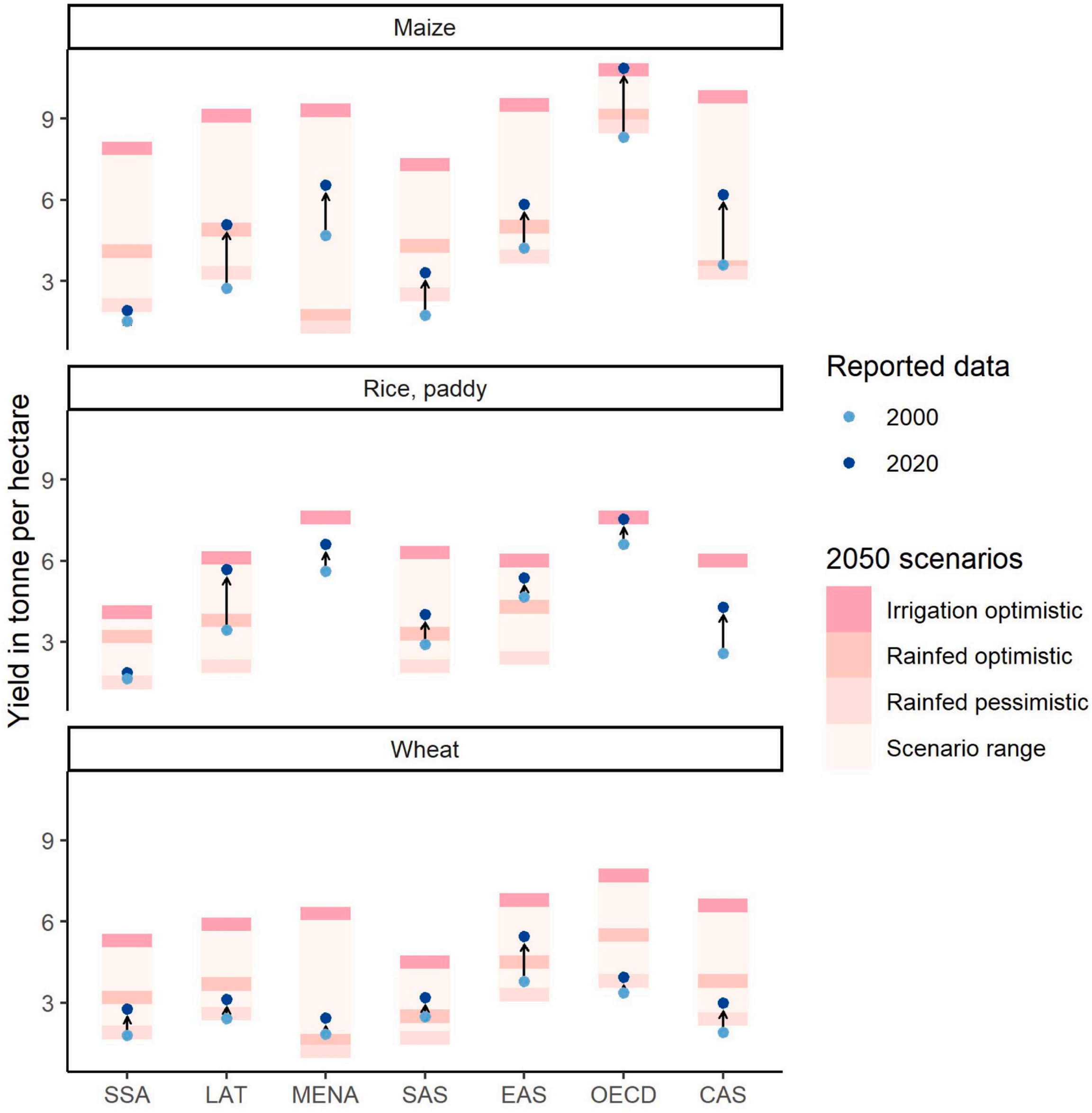

Fig. 4. Cereal yields in 2000 and 2020 (reported) and 2050 (projected). SSA is sub-Saharan Africa, LAT is Latin America, MENA is Middle East and North Africa, SAS is Southern Asia, EAS is Eastern Asia, OECD is OECD countries, CAS is Central Asia and Eastern Europe. Data source: FAOSTAT 'Crop production' and 'Crop area' for rice, maize and wheat; Comprehensive Assessment for yield targets in 2050 scenarios.

Mekonnen and Hoekstra, 2020). Intentions to minimally increase water consumption in irrigated agriculture have been undermined by quick allocation of 'gained' water to further expand and intensify agriculture, leading to higher water consumption overall (Grafton et al., 2018). Thus, the world has rapidly acquired more (blue) water for irrigated agricultural use, to the detriment of water availability elsewhere. Moreover, production in existing irrigated areas will increasingly fluctuate, as overstretched river basins and aquifers deliver less water for irrigation, and climate extremes aggravate both water supply and irrigation demand.

For maize, global production figures seem more positive. Significant increases in productivity are reported for 2020 (Fig. 4). Maize has benefited from production shifting from rainfed to irrigated areas and optimization of agronomic practices (Rizzo e al., 2022). But caution is called for, because at the global level only a small share of maize production (13 %) is directly used for food consumption. The majority (56 %) is destined for animal feed (Erenstein et al., 2022). The increase in maize production thus serves mainly to meet the rising global demand for animal protein. As the other avenues for optimizing land and water use – trade, rainfed agriculture and irrigated cereals – continue their pessimistic trend, the productivity increase in maize over the period 2000–2020 does little to keep agriculture and water within sustainable limits.

4. Discussion

These results point unmistakably to the conclusion that the anticipated gains in land productivity and water productivity and optimization of global trade have not materialized for 2000–2020. Instead, the world appears to be on a rather pessimistic path to produce sufficient food only with steadily increasing agricultural land and water use, at the direct expense of ecosystems. During 2000–2020, cereal yields increased slightly, by 31 % (whereas projections were in the 21–61 % range) or 1.38 % per year, and photosynthesis was not improved to enable more biomass to be grown with relatively less water (Araus et al., 2021). Global cereals trade, too, developed in a far from ideal pattern, as arable land in the OECD and Central Asia – key production areas for cereal trade – declined by 35 million hectares. Strong arable land expansion was found in Africa (+ 44 million hectares, with low yields), in Latin America (+ 19 million hectares, mainly for animal feed and biofuel) and in Eastern Asia (+ 11 million hectares, mainly irrigation expansion in China). Recent studies confirm this pattern of limited cereal yield gains (Rizzo et al., 2022; Gerber et al., 2024), abandonment of arable land in northern regions and expansion in southern regions (Winkler et al., 2021; Potapov et al., 2022; Zhang et al., 2022). The implication is that the world is able to produce enough food – though hunger remains – but only by using much more land and water and through restricted global trade, which all come at the expense of the natural environment. Based on this track record, optimistic scenarios of further large productivity gains for major cereals appear unlikely. Unconventional solutions are needed to divert the world from locking into this pessimistic path.

Some share our notion that the world is on a pessimistic path to produce sufficient food (Richardson et al., 2023), while others keep exploring potential gains to be had from trade and from productivity increases in rainfed and irrigated agriculture (Bayer et al., 2023) – though we find this unrealistic, given the poor track record of the past. Even recent flagship reports portray a more optimistic outlook than warranted considering the results of our study. Such misperceptions risk glossing over lessons from past experiences in optimizing land and water use. For example, FAO does not link the increasing share of water used for agriculture to declining water supplies for nature, and considers yield gaps closable (FAO, 2020), even though in the past 20 years limited yield gains were actually achieved, just above the pessimistic yield projections of the Comprehensive Assessment. Also, the IPCC concludes that adaptation options exist for water-related risks in agriculture (IPCC, 2023). While these options may exist in theory, in reality, the limited yield increases achieved strongly signal that maintaining land productivity – let alone increasing it – in a changing climate will form a major challenge in rainfed agriculture, particularly considering the likelihood of more extreme and fluctuating rainfall and temperatures. In addition, the sustainability of the growth path is unsure, as future performance of rainfed and irrigated agriculture is further undermined by widespread poor drainage affecting 130–200 million hectares (Castellano et al., 2019), soil salinity affecting 424 million hectares (Negacz et al., 2022) and unsustainable mining of groundwater affecting 40–50 % of all irrigated areas (Jägermeyr et al., 2017; Rosa et al., 2019; Mekonnen and Hoekstra, 2020).

Our study was limited in that we focused on productivity gains and did not assess alternative options to reduce the pressure of agriculture on land, water and ecosystems. We therefore end this article with three unconventional options for reducing the rising pressure of agriculture on land, water and ecosystems, while pursuing national, regional and global food security. These options can be brought together in initiatives to transform and enhance food security within landscapes and reduce dependence on global trade

First, reducing food demand is imperative, as nearly half of all arable land is used for livestock feed and biofuel (Muscat et al., 2020). A switch in most regions to a primarily plant-based diet (Willett et al., 2019) would significantly reduce future demand for feed, resulting in reductions in arable land with 19 % (Gibbs and Cappuccio, 2022) and water use with 12 % (Tuninetti et al., 2022). Cutting post-harvest losses and food waste, estimated at 24 % for cereals (Spang et al., 2019), would also reduce amounts of food to be produced by farmers. Reducing biofuel not only reduces demand for arable land, but also negative impacts of biofuel crops in relation to greenhouse gases, biodiversity and the environment (Tudge et al., 2021).

Second, the increasing impact of climate change on yields (Lesk et al., 2016; Zhu et al., 2022) has made farm profits more volatile. Yet, this has remained a blind spot in agricultural development and policy, which have mainly targeted maximization of yields and closing yield gaps. Instead, stable yields and stable profits in farming over multiple seasons should become a priority, particularly in rainfed agriculture, as the area under rainfed cereals is in decline and farmers are opting for higher value feed crops. A possible option could be 'diversification' (increase the number of crop and livestock species on a farm) as it buffers climate volatilities, diversifies production throughout the year, and brings environmental benefits such as increased biodiversity and other ecosystem services (Rasmussen et al., 2024).

Third, the importance of traditional landrace crops and varieties should be reassessed and used to broaden the crop genetic resources base. These traditional varieties are generally more robust to climatic extremes and seasonal variations (Mayes et al., 2011; Dwivedi et al., 2016), in addition to being nutritionally rich (Nyathi et al., 2019, Jamnadass et al., 2020). They could thus provide greater nutritional food security in high-stress environments when water and nutrients are limited and temperatures turn high.

5. Conclusion

This paper reviews global efforts to optimize agricultural land and water use so that more food can be produced with relatively less land and water while protecting nature. The analysis undertaken here shows that post-Green Revolution gains in productivity have significantly slowed and are in danger of stagnating. Specifically, for the period 2000–2020, only slight gains in agricultural productivity were achieved compared to what was anticipated in the Comprehensive Assessment in 2007. With such relatively small gains the world will fall short against its target and needs of food and water security without significant systemic shifts in our agricultural food systems. Equally our natural environment and the nature it supports will also continue to be degraded. The main options for changing these agricultural and food systems into a more efficient and sustainable approach involves a multipronged approach to:

- change, for large parts of the world, to a diet in which plant based calory-intake are more prevalent
- reduce food waste along the value chain from farm production to the point of consumption
- tackle how to increase productivity against a changing climate and associated shocks
- increase the use of underutilised, often more traditional type crops and produce.

This approach signifies the need to reorient the Water for Food debate from a focus on 'crop per drop' to 'nutritional crops for planet-sustainable diets and food consumption' as the past optimism on technological and agronomic fixes to reduce consumptive water use in agriculture is not yielding enough progress. The multipronged approach is possible but requires strong coordinated leadership and governance at a global level to divert the world from the unsustainable path of using steadily more land and water to produce food and feed at the expense of nature. Effective implementation in the coming decades, for instance by incentivising farmers for large parts of the world to produce food crops rather than biofuel or fodder crops, might just provide a turn-off from the pessimistic path that developments in agriculture and water are now taking.

CRediT authorship contribution statement

Chris Seijger: Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Anton Urfels:** Writing – review & editing, Visualization, Formal analysis, Data curation. **Maria Christoforidou:** Writing – review & editing, Visualization, Formal analysis, Data curation. **Petra Hellegers:** Writing – review & editing, Methodology, Conceptualization. **Gerlo Borghuis:** Writing – review & editing, Investigation, Formal analysis. **Simon Langan:** Writing – review & editing, Methodology, Conceptualization. **Gerardo van Halsema:** Writing – review & editing, Writing – original draft, Formal analysis.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2024.109229.

Data availability

Data used in analysis is in the Supplemental File we provide with the manuscript.

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