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Mind the gap: how do climate and agricultural management explain the 'yield gap' of croplands around the world?

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ABSTRACT

Aim As the demands for food, feed and fuel increase in coming decades, society will be pressed to increase agricultural production – whether by increasing yields on already cultivated lands or by cultivating currently natural areas – or to change current crop consumption patterns. In this analysis, we consider where yields might be increased on existing croplands, and how crop yields are constrained by biophysical (e.g. climate) versus management factors.

Location This study was conducted at the global scale.

Methods Using spatial datasets, we compare yield patterns for the 18 most dominant crops within regions of similar climate. We use this comparison to evaluate the potential yield obtainable for each crop in different climates around the world. We then compare the actual yields currently being achieved for each crop with their 'climatic potential yield' to estimate the 'yield gap'.

Results We present spatial datasets of both the climatic potential yields and yield gap patterns for 18 crops around the year 2000. These datasets depict the regions of the world that meet their climatic potential, and highlight places where yields might potentially be raised. Most often, low yield gaps are concentrated in developed countries or in regions with relatively high-input agriculture.

Main conclusions While biophysical factors like climate are key drivers of global crop yield patterns, controlling for them demonstrates that there are still considerable ranges in yields attributable to other factors, like land management practices. With conventional practices, bringing crop yields up to their climatic potential would probably require more chemical, nutrient and water inputs. These intensive land management practices can adversely affect ecosystem goods and services, and in turn human welfare. Until society develops more sustainable high-yielding cropping practices, the trade-offs between increased crop productivity and social and ecological factors need to be made explicit when future food scenarios are formulated.

Keywords

Agricultural land, agricultural system, climate, crop yield, cropland, global, land management, global land use, yield gap.

INTRODUCTION

Today, croplands are one of the most extensive ecosystems on Earth, stretching across *c.* 12% of the planet's ice-free land surface (Leff *et al.*, 2004; Ramankutty *et al.*, 2008). Altogether, global croplands also represent 10–15% of the total biological productivity of the planet (Haberl *et al.*, 2007). However, society is still looking for ways to dramatically increase crop production, as population and economic pressures continue to mount through the 21st century. Changes in lifestyles and a shift away

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from diets heavy in grain-fed meat would be likely to relieve some of this pressure. Still, additional food, feed and biofuels will need to be produced if we are to provide for the additional 2.2 billion people that are projected to inhabit the planet by 2050 (UN, 2005). Already, we are expecting to need at least 50% more agricultural production by 2050 (Tilman *et al*., 2001).

Increasing global crop production will be one of the greatest challenges facing humanity in the coming decades. On the surface, there appear to be two broad options for increasing global food production: (1) expand the area of croplands at the expense of other ecosystems, or (2) increase the yields (per unit area) of our existing croplands. Ramankutty *et al.* (2002) showed that we are cultivating roughly half of the land that is suitable for agriculture on the planet today. However, the study also showed that much of the remaining cultivatable land rests under the tropical rain forests of South America and Africa – biomes that are of high social, economic and ecological value. Therefore, improving the yield on existing agricultural lands is a high priority.

However, increasing crop productivity on existing lands will also have consequences for social and ecological systems if we continue practising some of the techniques of modern industrialized agriculture. At present, much of our high-yielding agricultural lands are monocultures that receive high levels of water and chemical inputs, practices that have adverse impacts on water quality, soil quality and biodiversity (Matson *et al*., 1997; Tilman *et al*., 2002; Foley *et al*., 2005). It is critical that creative and novel approaches be taken to ensure that in our pursuit of increasing yields we do not carry our most ecologically destructive agricultural practices into the future.

In order to understand our prospects for increasing crop yields in the future, we must first understand what controls the tremendous variation of crop yields we see across the world today.

Today's geographic patterns of crop yields are clearly influenced both by climate and agricultural management practices. As shown by Lobell & Field (2007), climate exerts considerable control over the yields obtained from croplands. In their study, Lobell and Field found that approximately 30% of the annual variation in globally averaged yields of the six crops included in the analysis could be attributed to climate variables. At the same time, this result highlights the importance of other factors in explaining crop yields.

In this study, we analysed global agricultural yield patterns and examined their dependence on climate and land management. Large differences in these yields have already been identified (Johnston *et al.*, 2009). Here we developed a methodology for quantifying and spatializing productivity gaps – a methodology that will also be used in a parallel study quantifying biofuel potential from intensification (M. Johnston *et al.*, University of Wisconsin-Madison, WI, USA, unpublished data). We utilized new, globally gridded yield datasets for 18 major crops in conjunction with globally gridded climate datasets to separate agricultural yields into 100 different climate zones. By analysing the resulting variations of agricultural yield within a given climate zone we were able to distinguish the effect of climate from other crop yield drivers, like soil quality, genetics and, of particular interest in this study, land management. Maps for the four most extensive crops are provided throughout the paper, those for the remaining 14 can be found in Appendices S1(a,b), S2(a,b) and S3(a,b) in Supporting Information.

This is the first detailed global analysis of how environmental and management factors influence agricultural yield. Based on this analysis, we can better address how changes in management – through conventional practices like irrigation, fertilizer use and mechanization, or implementation of alternative practices like agroecological methods that encourage nutrient recycling and natural pest control – could potentially increase yields in many parts of the world (Altieri & Rosset, 1996; Tilman *et al*., 2002).

METHODS AND RESULTS

Current crop yields

The new global crop datasets from Monfreda *et al*. (2008) document the harvested area and yields for 175 crops around the world for the year 2000 (Fig. 1). The datasets represent agricultural conditions on a $5' \times 5'$ (approximately 10 km × 10 km) geographic grid of the planet. These datasets were created by merging a detailed library of global census data (from the national, state and county level for over 20,000 political units) with three different, detailed satellite datasets of global land-cover conditions. Thus while the data for yield and area harvested are presented at a $5'$ resolution, they were originally reported at varying, coarser resolutions. Still, this is by far the most complete description of agricultural landscapes – including the area and yield of a large number of crops – for the planet today.

The crop yield and area harvested data represent conditions around the year 2000. To account for inter-annual variability resulting from factors like weather, Monfreda *et al*. (2008) averaged area harvested and yield data for the years 1997–2003, when available. These data therefore represent a snapshot of global agricultural production at the 2000 epoch (1997–2003), not the year 2000 per se.

In addition, while the Monfreda *et al*. (2008) datasets are the best available global crop yield datasets, it is possible that there are some sources of error that could potentially influence our results. For example, since limited biophysical and topographic parameters were used in the mapping of croplands and their respective yields over space, it is possible that crop yields may have been distributed onto occasional grid cells with unsuitable growing conditions according to the climatology datasets used in this study. It is thus important that these datasets be used to address issues related to their intended purpose: to compare *regional* crop yield patterns, rather than to investigate trends on individual grid cells.

In this study, we used the Monfreda *et al*. (2008) data for 18 major crops: maize, wheat, rice, soybean, barley, millet, rye, sorghum, cassava, potato, sugarcane, sugar beet, groundnuts, oilpalm, rapeseed or canola, cotton, pulses and sunflower. We

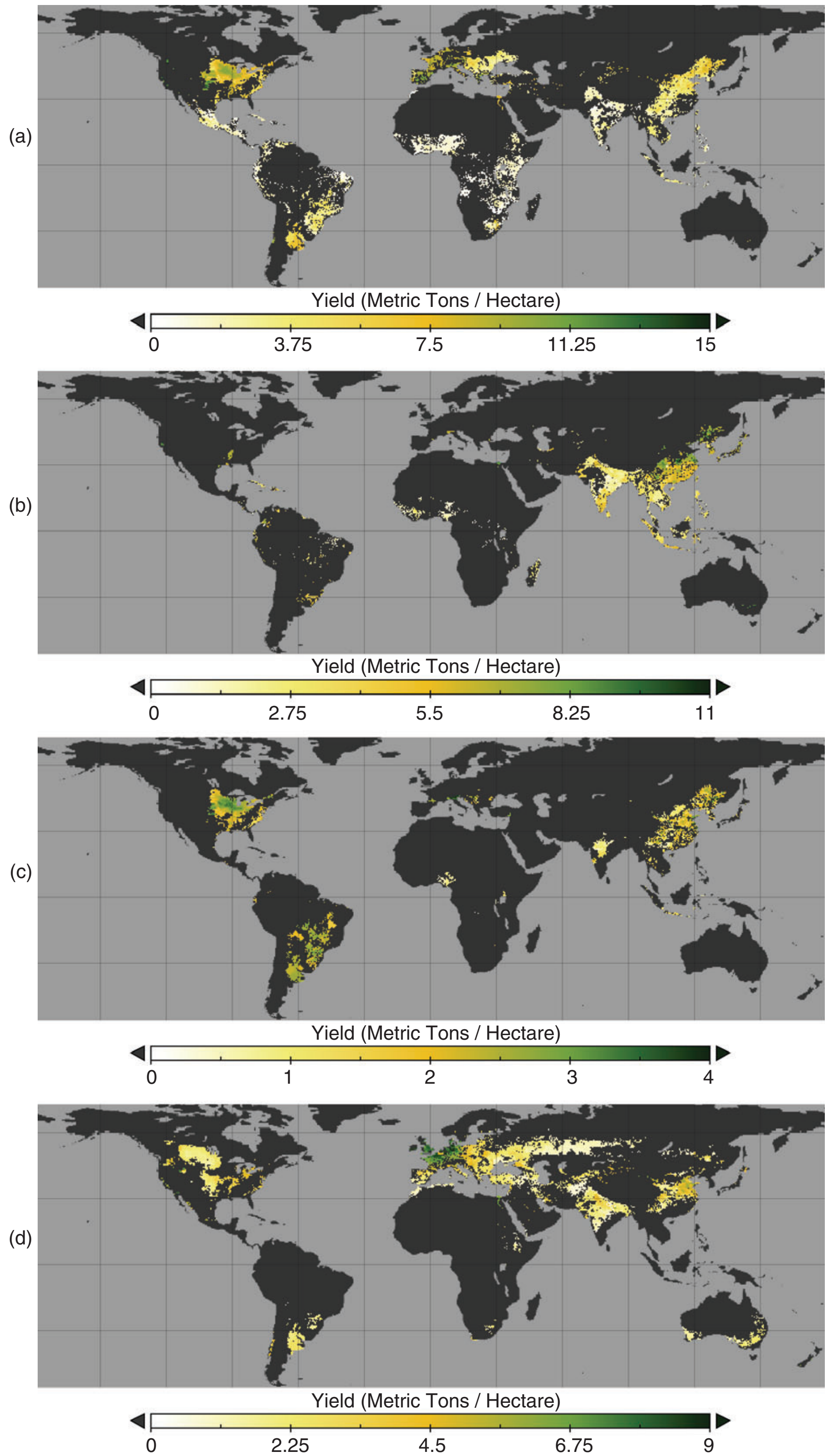

Figure 1 Global crop yields in metric tons ha^{-1} on a 5′ grid with an equirectangular projection for (a) maize, (b) rice, (c) soybean, (d) wheat (data from Monfreda *et al.* 2008).

concentrated on these crops because together they constitute *c.* 85% of the world's croplands (Leff *et al.*, 2004).

All of the crops included in this study cover large extents of the Earth's surface. Some crops, like maize and wheat, are dietary staples and important cash crops across many different cultures. As a result, they are grown at a large scale in many regions, covering *c.* 13% and *c.* 22% of the Earth's cultivated lands, respectively (Leff *et al.*, 2004; Monfreda *et al.*, 2008).

The Great Plains of the United States and Canada, south-central Asia, Australia, eastern Asia, eastern and western Europe, Argentina and Brazil all stand out as wheat hotspots as large swaths of their agricultural lands are devoted to the crop (Monfreda *et al.*, 2008). Most of the highest-yielding wheat cropland is located in western Europe, as well as the western United States (Fig. 1d).

Second to wheat in global coverage (Leff *et al.*, 2004), maize is mainly grown in the mid-western United States, Brazil, southern Africa, eastern Europe, Asiatic Russia and north-eastern China (Monfreda *et al.*, 2008). Of these maize hotspots, the yields in the Mid western United States exceed those obtained in the other regions. Still higher maize yields can be found in the western United States, although maize cultivation in the western United States is not as concentrated as in the Midwest (Fig. 1a).

The regions with the most extensive cultivation of a single crop may not necessarily be the regions with the highest yields. For example, the most extensive areas of cotton production are found clustered around the Gulf of Khambhat in India, along much of the India–Pakistan border and in the central and eastern parts of the United States (Monfreda *et al.*, 2008). However, some of the greatest cotton yields are found in the south-western United States, around the Mediterranean Sea and in China (Appendix S1a). Similarly, millet, an important grain for some developing countries, is largely grown in a strip extending across western and Central Africa, the Indo-Gangetic Basin and across western India. In contrast, the highest yields occur in eastern China and the United States (Appendix S1a).

The cultivation of some crops, like soybean, is more concentrated. While the major soybean hotspots in terms of cultivated area include Brazil, Argentina and India, the mid-western United States achieves the highest yields and thereby accounts for much of the global production (Fig. 1c).

Measuring how global crop yields are influenced by biophysical factors

The world's crop yield patterns are controlled by a variety of factors, including climate, soil quality, genetic potential and human management (including irrigation, fertilization and other planting practices). The availability of the Monfreda *et al.* (2008) agricultural datasets provide an opportunity to begin comparing global crop yields and investigating their drivers in a more comprehensive way than has previously been possible.

To understand the relative influence of these different drivers on crop yields, we first grouped and compared crop yields from similar climates. We examined the global crop yield data in conjunction with global, gridded monthly climatology data (New *et al.*, 2002) and interpolated them from a 10′ to 5′ spatial resolution. We then separated agricultural croplands into 100 different climate zones and compared crop yields within a given climate zone.

This remapping of crop yields into climate zones allowed us to control for the effect of climate, and to isolate variations in yields attributable to other yield drivers, such as land management. For example, in our analysis, crop yields from Madison, WI, were compared with regions around the world with similar climates (including parts of north-eastern China, southern Germany, Bosnia, and central Russia) – so that yields in Madison may be evaluated against other croplands of the world that experience the same basic climatic conditions. By 'levelling the climatic playing field', we considered how differences in management (or other factors, such as soil conditions) affect yields within similar climates.

When mapping crop yields, we focused our analysis on the major crop-growing regions around the world. To filter out grid cells that are not a part of the major growing regions for each crop, we sorted the grid cells based on the fraction of the grid cell occupied by the given crop. We then performed our analysis on the grid cells that comprise the top 95% of the global area for that crop; the remaining 5% of cumulative cropland area (i.e. in the most sparse agricultural lands) were removed from further consideration.

Examining the effects of climate on yield

While there are multiple ways in which climate can be classified, we followed the logic of Prentice *et al.* (1992), who described relationships between climate and global biomes. We used two parameters known to be fundamental drivers of plant growth to describe a region's climate – growing degree days (GDD) (Fig. 2) and a crop soil moisture index (the ratio of actual evapotranspiration to potential evapotranspiration) (Fig. 3).

We calculated GDD as in Ramankutty *et al.* (2002), with

$$\mathrm{GDD} = \sum_{i=1}^{365} \max(0, T_i - T_\mathrm{b})\,\mathrm{days-degrees} \quad (1)$$

where T_i is the temperature in °C at each time step and T_b is a crop-specific baseline temperature. For those crops generally grown in warmer climates (cassava, cotton, groundnut, maize, millet, oilpalm, sorghum, soybean, sugarcane and sunflower), we used a T_b of 8 °C, whereas we used a T_b of 2 °C for those crops also found in cooler regions (potato, pulses, rapeseed, rye and sugarbeet). We use an observed T_b of 0 °C for wheat, 1 °C for barley and 5 °C for rice (Hodges, 1990).

We then calculated the crop soil moisture index as the ratio of actual evapotranspiration to potential evapotranspiration (AET/PET), similar to Prentice *et al.* (1992) and Ramankutty *et al.* (2002) (see Appendix S4).

Building on methodology developed in Zaks *et al.* (2007), we created a 10 × 10 matrix of GDD and average, annual crop soil moisture availability with 100 different climate zone combinations. For each axis of the matrix, we divided the GDD and crop

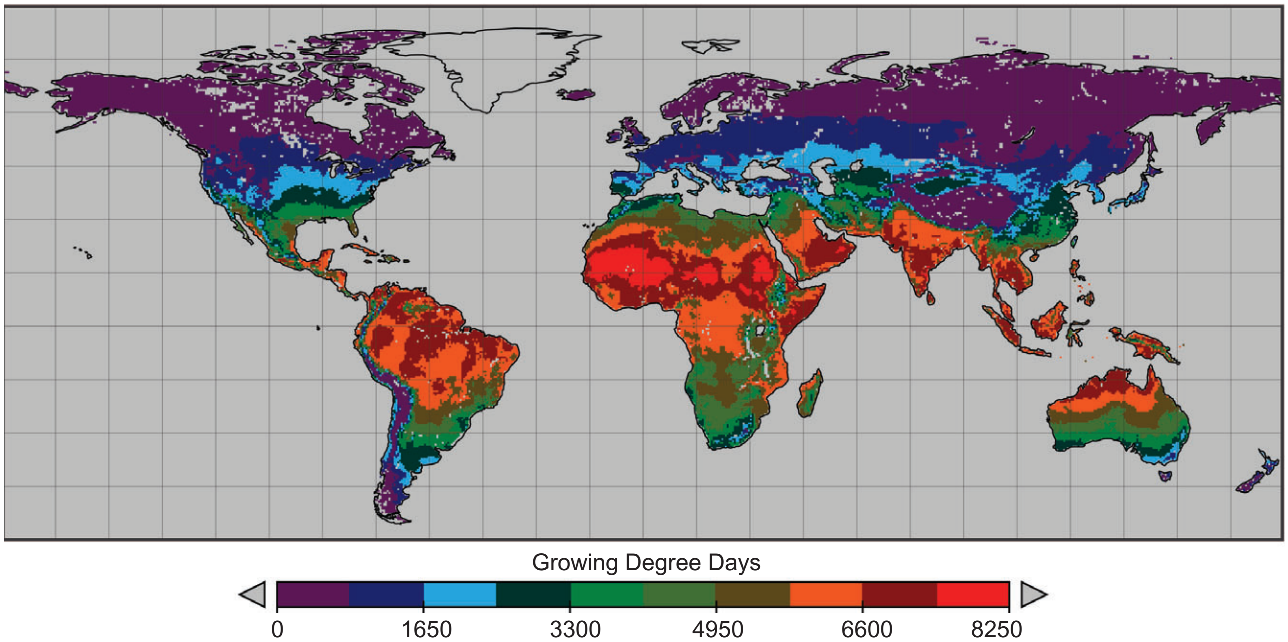

Figure 2 Global growing degree day (GDD) values, baseline temperature 8 °C, on a 5′ grid with an equirectangular projection.

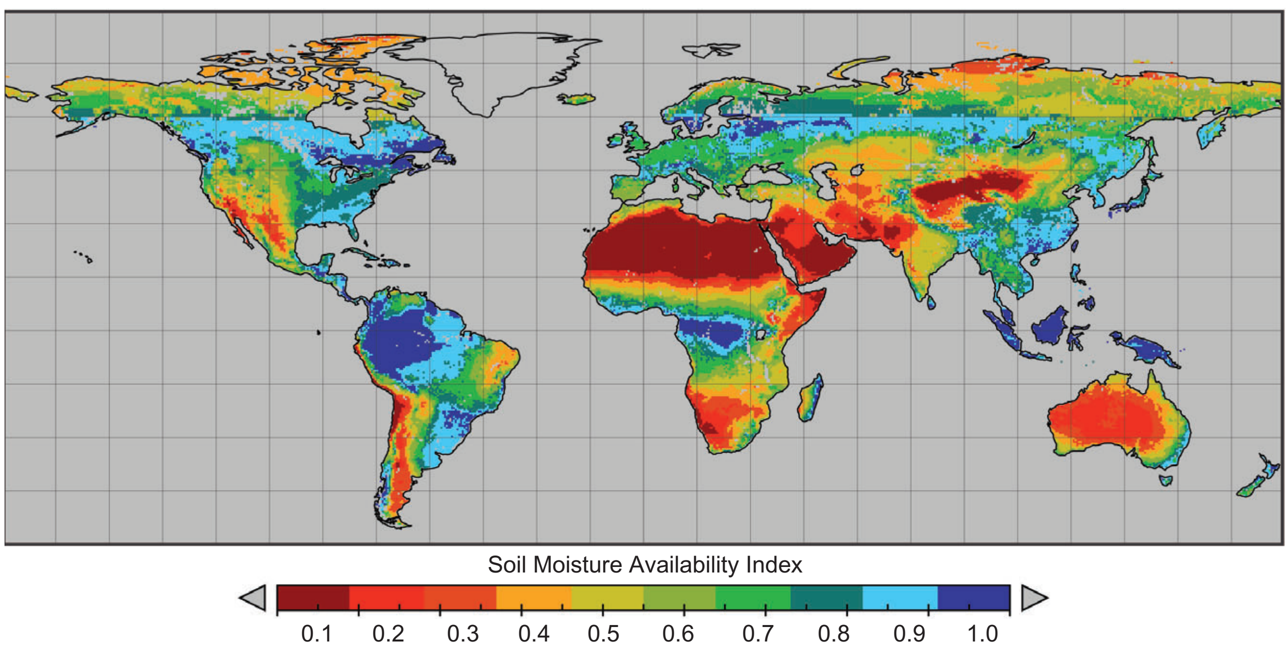

Figure 3 Global crop soil moisture index values on a 5′ grid with an equirectangular projection.

soil moisture index data, respectively, into 10 equal parts. For example, because the crop soil moisture index data ranged from 0 to 1, the bounds of soil moisture in the first 'bin' of the matrix were 0 and 0.1. For a crop like wheat with a baseline temperature of 0 °C, because the maximum number of growing degree days above 0 °C on Earth is approximately 11,168, the bounds of GDD for the first bin were approximately 0 and 1117 days; the number of GDD per bin varied depending on the baseline temperature used. We then assigned each grid cell to one of the 100 climate zones (Fig. 4), based on its GDD and crop soil moisture conditions.

We subsequently distributed the yields from each grid cell, crop by crop, into their respective climate zones. By doing so, we obtained a distribution of yields for each crop in each climate zone. To ensure that we had a statistically meaningful number of yield observations in each climate zone, we imposed a five-datapoint threshold for the yield distributions. If there were not yield observations from at least five different grid cells, we did

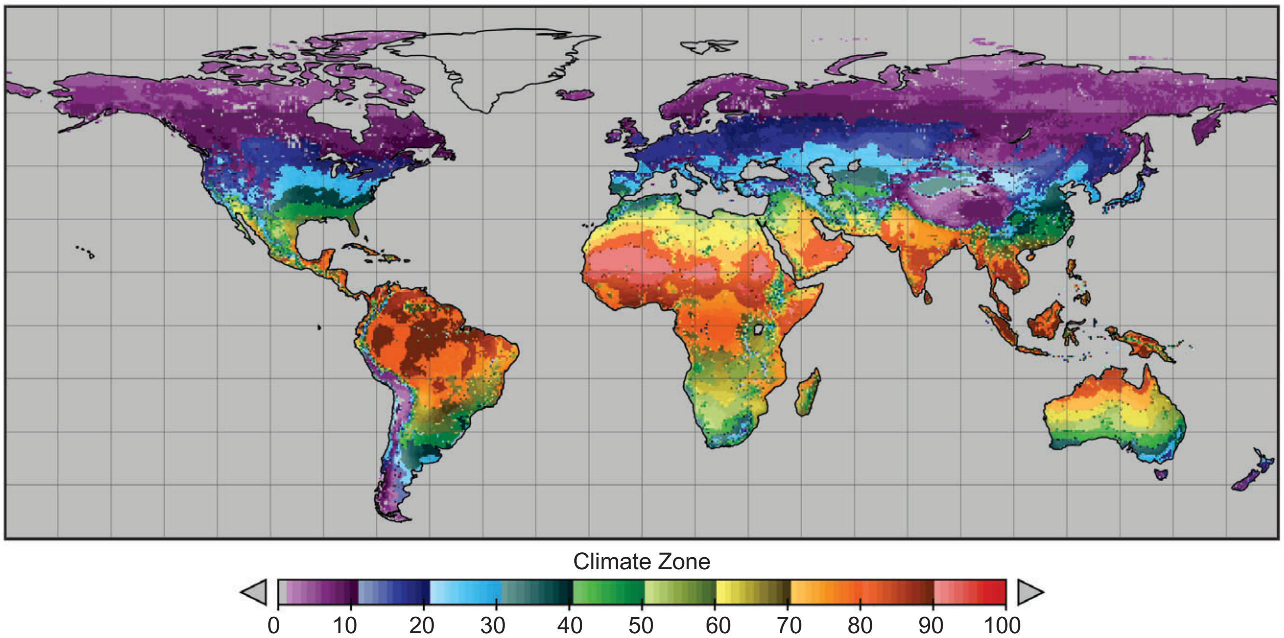

Figure 4 Location of 100 climate zones on a 5′ grid with an equirectangular projection.

not include the climate zone for that crop in our analysis. However, the number of observations in each climate zone distribution varied depending on the climate each crop is typically grown in. For example, oilpalm is typically grown in warm, humid climates; there were few to no observations in other climate zones.

For each climate zone and each crop we generated a table containing the yield, harvested area and latitude/longitude position information for each grid cell included in the distribution. We then sorted the data from the grid cells by their yield values, ranking them from lowest yield to highest. Next, starting with the grid cell with the lowest yield value, we accumulated the grid cells' respective harvested areas, until we arrived at the statistical information of interest: the mean, median and 90th percentile yields. We then used the respective yield data from that point to define the mean, median and 90th percentile yields. (Other statistical properties, such as the 25th and 75th percentile yields can also be calculated with this method.) With this approach, we defined a percentile yield value by accumulating that percentage of a crop's harvested area, rather than that percentage of a crop's yield observations. This allowed us to prevent grid cells with smaller amounts of cultivation from skewing the results.

For our analysis, we were interested in defining maximum potential yield values. We chose to concentrate on the 90th percentile yield value for each climate zone as a 'climatic potential yield'. We did not use values above the 90th percentile to define the maximum in order to avoid erroneous or overestimated values that may have been included in the yield datasets.

From this analysis, we mapped the global patterns of climatic potential yield (i.e. the 90th percentile yields from each climate zone, remapped across the globe). Figure 5 shows these climatic potential yields, representing what we believe is a reasonable estimate of the 'maximum' yields achievable today – given the modern distribution of yields across the different climate zones of the planet.

Of course, this does not mean that these yields are the absolute 'maximum' yields a crop will ever be able to achieve. Rather, they simply represent the maximum, climatic-potential yields currently being achieved on croplands in any given climate zone in the world in around 2000, with management practices and varieties that have already been adopted by farmers. As the yield data in this study were derived entirely from agricultural inventory statistics, it is possible that higher yields might be found on, for example, experimental research plots. In addition, further advances in biotechnology, seed genetics and agricultural technology may further boost maximum yields far beyond what we see today. However, our results represent the maximum achievable yields given today's technology, using best management practices and high-yielding crop varieties, for each climate zone. We focus on those yields that have already been shown to be obtainable by farmers with methods and tools that have already been found to be adoptable. These results help illustrate where we can potentially increase yields *today* – without any major advances in crop genetics or biotechnology – by adopting agricultural practices that are already used in other places.

It is important to note that it is possible that some climate zones may only include agricultural lands that are seemingly low-yielding for a particular crop relative to what is thought possible for a given climate. This may be the result of the respective farmers lacking access to high-yielding crop varieties and/or an inability to carry out best management practices. If all of the yield data are low in a climate zone some climatic potential yields may appear unexpectedly low.

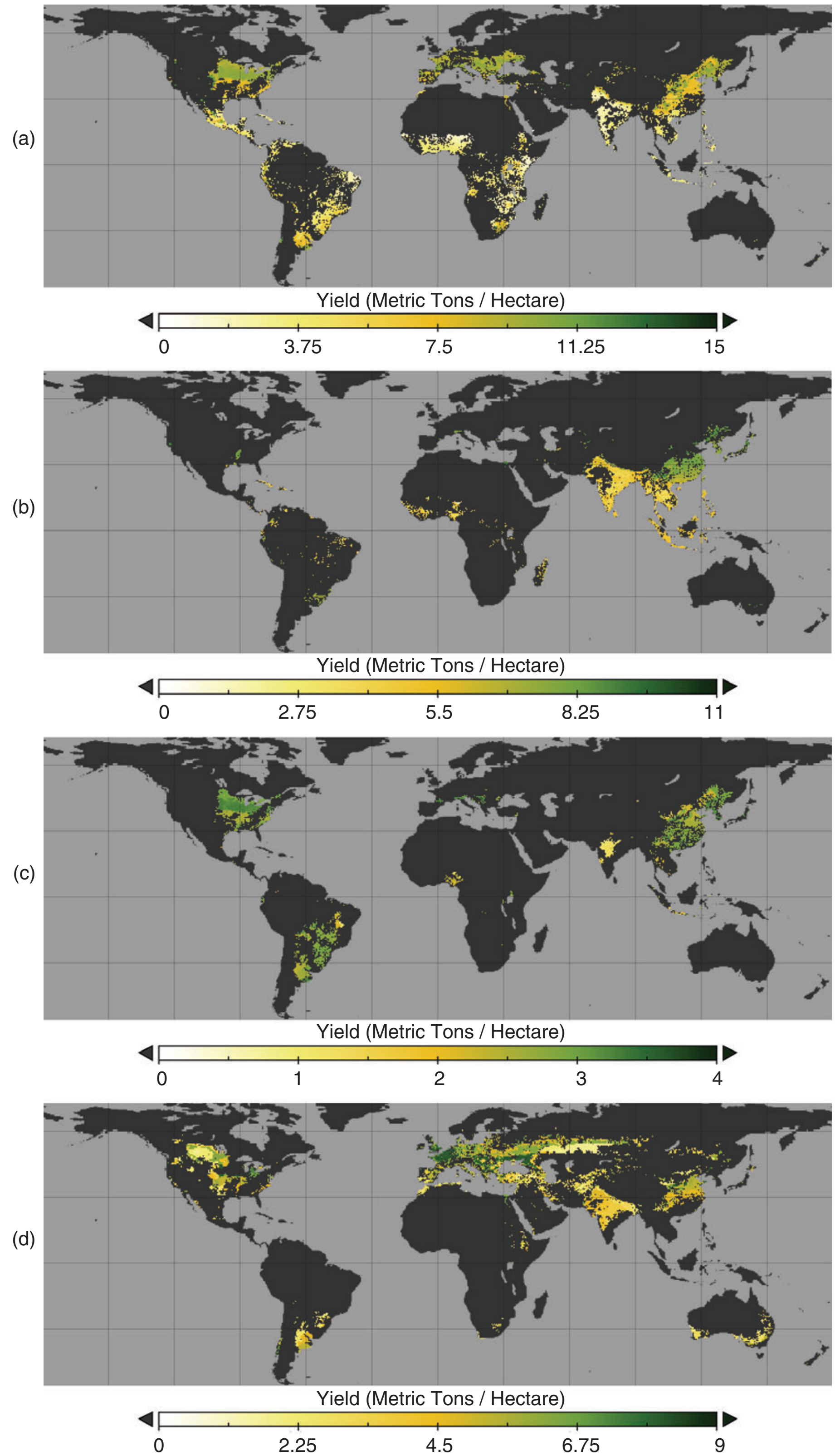

Figure 5 Climatic potential yield values in metric tons ha^{-1} on a 5′ grid with an equirectangular projection for (a) maize, (b) rice, (c) soybean, (d) wheat.

Of the places currently cultivating a crop, we can see from the climatic potential yield maps (Fig. 5) those places that have a climate able to support high yields. For example, parts of the US and Canadian plains, as well as the eastern United States, much of Europe, and parts of eastern China have climates well suited for high wheat yields (Fig. 5d). The second most dominant crop, maize, shows similar patterns, with most of the potentially high-yielding lands concentrated in the mid-latitudes (Fig. 5a). The northern United States, Europe, both east and west, as well as parts of eastern China, all have a high climatic potential for maize.

Cotton also shows strong latitudinal patterns, with much of the potentially high-yielding lands concentrated between 30 and 45° N (Appendix S2a). Australia and parts of southern Africa also have high climatic potential cotton yields.

Several of the crops included in this study demonstrate a high climatic potential yield in the United States, Europe and/or eastern China. For example, Europe and north-eastern China show high climatic potential yields for rye (Appendix S2b). The central and south-eastern United States and eastern China have the potential for high groundnut yields (Appendix S1a). Soybean potential is highest in the eastern United States, southern Europe, much of eastern China as well as in Brazil and Argentina (Fig. 5c).

Other crops have a higher climatic potential elsewhere. Parts of South America, Mexico and the southern United States, as well as parts of eastern Africa, along the River Nile, and Australia have high climatic potential yields for sorghum (Appendix S2b). Peru, India and parts China and Africa are home to the highest potential sugarcane yields (Appendix S2b). The highest climatic potential yields for cassava can be found in southern India, Southeast Asia, parts of South America and western Africa (Appendix S2b).

Considering the effects of soils on yield

In addition to examining the effects of climate on global crop yield patterns, we sought to incorporate soil conditions into our analysis so as to control for the effect of soil types on yields and broaden our consideration of biophysical factors.

In fact, we already use soil information in our analysis: soil texture properties are used in the calculation of soil moisture, which in turn influences the moisture availability index in our climatic analysis. We had hoped to further include the effects of soil 'quality' in relationship to agricultural yields.

In order to do this, we used the ISRIC 5′ × 5′ datasets of soil pH and organic carbon for the top 20 cm of soil (Batjes, 2006). We posit that variations in soil pH and soil organic matter are the best available proxies for soil quality and tilth on a global scale (Ramankutty *et al.*, 2002), especially given the relatively poor state of information on global soils.

To separate the influence of soils from that of climate (especially since the two may be strongly correlated), we needed to examine the relationship between yield and soils within each of our 100 climate zones. Such an exercise quickly revealed that we have insufficient samples within each climate zone to build robust statistical relationships (indeed, our sample size was already quite limited even when the analysis was restricted to just climate).

While it might be possible to derive crop-specific functions that relate soil conditions and yield, it is beyond the scope of the current analysis. Here we aim to develop a growing condition scheme that is complete enough to organize the world into climatic classes that are accurate and meaningful, yet simple enough to be distinct. Further study will be needed to quantify the crop-by-crop relationships between soil chemistry and yield, as no general, global relationships emerged from our analysis.

Calculating global 'yield gaps'

In our analysis, we define the 'climatic potential yield' as the 90th percentile yield achieved for a given crop in a given climate zone. The 'actual yield' is the yield actually observed in a given location, which may be significantly different than the climatic potential yield. From these, we define the *yield gap*:

$$\text{yield gap} = \text{climatic potential yield} - \text{actual yield} \tag{2}$$

and the *yield gap fraction*:

$$\text{yield gap fraction} = 1 - (\text{actual yield}/\text{climatic potential yield}). \tag{3}$$

The yield gap fraction (a value from 0 to 1) tells us how close to the climatic potential any given location may be. Those places with a low yield gap (close to zero) have yields at or near their climatic potential.

More often than not, developed countries have low yield gaps. This is especially true for maize, wheat, potato, rapeseed, rye and sunflower in western Europe (Fig. 6a,d, Appendix S3a,b), as well as maize and soybean in the United States (Fig. 6a,c). A notable exception to this is the cluster of high wheat yield gaps in the US and eastern Canadian plains – both of which stand in contrast to the low yield gaps of the western Canadian plains (Fig. 6d). When high yield gaps occur in western Europe, they are often concentrated in southern countries like Spain, Portugal and Italy.

The low yield gaps of western Europe often come to an abrupt halt at the border with eastern Europe. The yield gaps for most crops – including maize, wheat, barley, rapeseed and sunflower – are quite high in eastern Europe (Fig. 6a,d, Appendix S3a,b). Yield gaps are also generally high for potato and rye in eastern Europe, although some low yield gaps also occur in the region (Appendix S3a,b).

Overall, yield gap patterns tend to be more variable in Asia than in western Europe and the United States. However, clusters of low yield gaps do exist, such as in and around the more populous provinces of China – for example, rice, wheat, millet, potato and rye (Fig. 6b,d, Appendix S3a,b) – as well as in some parts of the Indo-Gangetic Basin – for example, rice, wheat and rapeseed (Fig. 6b,d, and Appendix S3b).

Yield gaps across Africa are on the higher end of the spectrum for many crops, especially maize and rice (Fig. 6a,b). When lower yield gaps appear, they tend to be concentrated in a strip

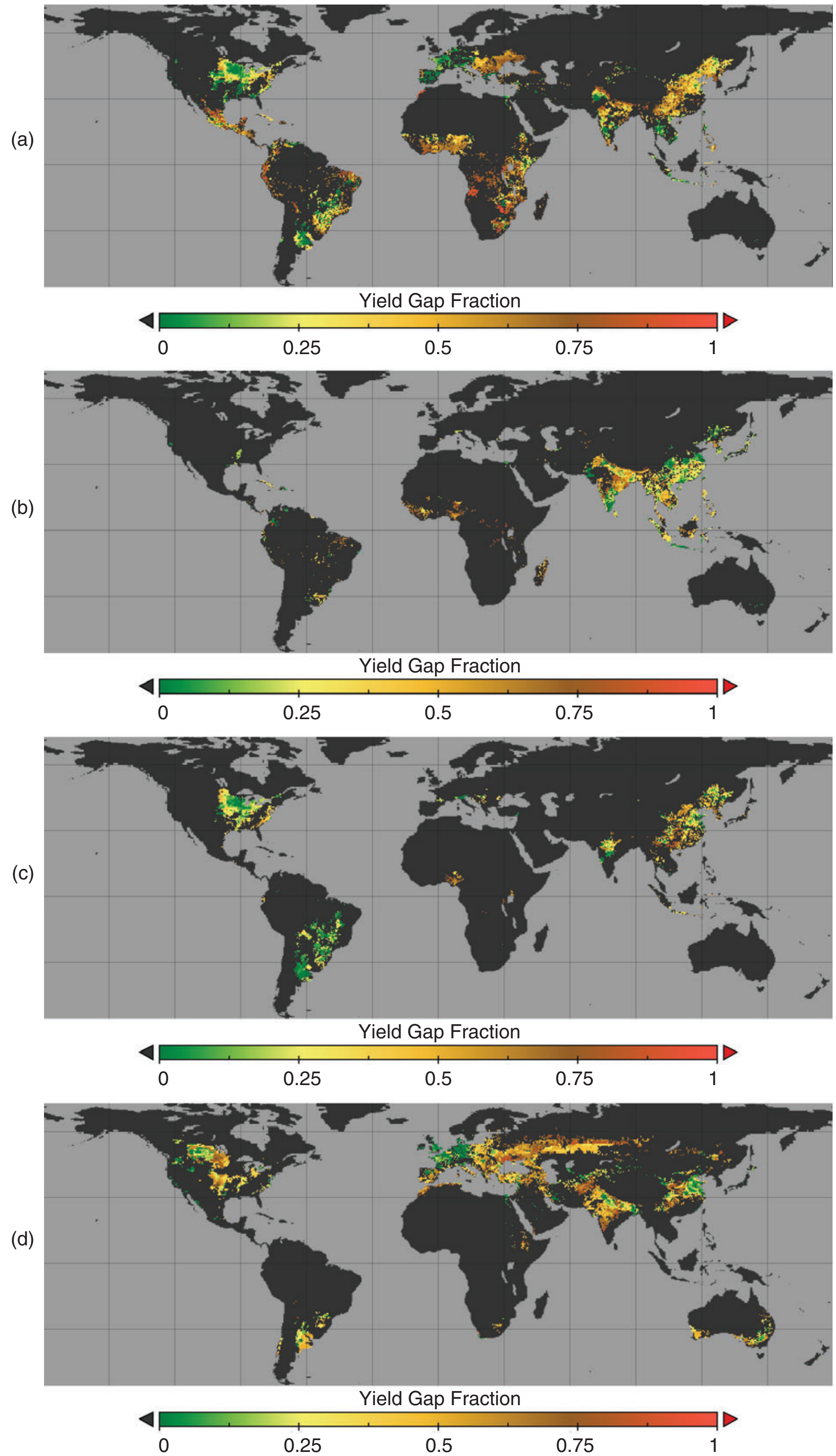

Figure 6 Yield gap fraction values on a 5′ grid with an equirectangular projection for (a) maize, (b) rice, (c) soybean, (d) wheat.

extending across parts of western and Central Africa, for example for cotton, millet, groundnut and sorghum, and across southern Africa for potato and sunflower (Appendix S3a and Appendix S3b). Cassava and pulses have generally low yield gaps throughout much of the continent (Appendix S3a,b).

Yield gaps are consistently low for soybeans in Central and South America (Fig. 6c). Sugarcane yield gaps are variable, but often low in the region (Appendix S3b). In contrast with the United States, Mexico's maize yield gaps are consistently high (Fig. 6a). Low maize yield gaps are concentrated in Brazil and Argentina.

Possible anthropogenic drivers of yield patterns

While the drivers of some yield gap patterns in the datasets may not be immediately apparent, it is clear that many follow political boundaries. For example, western and eastern Europe share similar climates, as can be seen in the GDD and crop soil moisture index maps (Figs 2 & 3, respectively). Yet western Europe displays considerably lower wheat and maize yield gaps than those of eastern Europe (Fig. 7a,b). In this case, the line dividing the high and low yield gaps does not follow biophysical borders but those of nation-states. Because climate has been controlled for, the difference in yields must be attributed to some other factors, most likely differences in agricultural management between western and eastern Europe around the year 2000.

Following the collapse of the Soviet Union, the yields of several crops important to the region, including maize and potatoes, declined (Trueblood and Arnade, 2001). The decline in productivity has been attributed to several factors, including a decrease in fertilizer use that followed the removal of fertilizer subsidies and an increase in fertilizer prices (Trueblood and Arnade, 2001); fertilizer use fell by 86% between 1990 and 2000 (Liefert *et al*., 2003). In addition, the deterioration of the former Soviet countries' extension services hampered farmers' access to the latest information and technologies, which compromised crop productivity in the region (Trueblood and Arnade, 2001). Coupling the yield gap maps with such information on Russia's fertilizer use demonstrates the potential that the region may have to increase its productivity by changing land management practices. These patterns also demonstrate how the differences in agricultural land management between nation-states are an important driver of global yield patterns, even relative to larger-scale biophysical phenomena, like climate.

To begin to understand the effect that agricultural management practices have on geographic variations in crop yields, and to explore the potential that countries may have to close their yield gaps, it is useful to employ global land management datasets, like Siebert *et al*.'s (2007) map of the percentage of land equipped for irrigation (Fig. 8).

This map demonstrates that irrigation infrastructure is most widespread in the Indo-Gangetic Basin – a region that, as discussed above, has low yield gaps for water-intensive crops like rice and cotton. High levels of irrigation infrastructure also coincide with the low yield gaps (for example, rice, wheat and cotton) found in China (Fig. 6 and Appendix S3b).

However, comparing the yield-gap analysis and irrigation data also demonstrates that the two are not perfectly correlated. For example, maize found in grid cells in eastern China generally has high yield gaps, although this region is heavily irrigated. In addition, while some parts of the extensively irrigated Indo-Gangetic Basin have low yield gaps, other portions exhibit high yield gaps. It is likely that irrigation is not the only management practice driving yield gap patterns in these regions. For example, there are probably differences in how fertilizers and pesticides are employed.

In addition, multiple crops often occupy a grid cell. So while it is possible to find maize with high yield gaps in a grid cell that has high levels of irrigation, it is possible that the irrigation is used for another crop. Conversely, a crop with a low yield gap could occupy a grid cell with seemingly low levels of irrigation, but what irrigation there is could be concentrated on that crop.

A subsequent study should tease apart and quantify the influence of different management practices such as irrigation and fertilizer use, as well as alternative agroecological methods, on global yield patterns. Other biophysical parameters such as soil quality and topography that were not taken into consideration in this study but may influence some of the observed yield gap patterns should also be considered further.

DISCUSSION

In this paper, we examine the global patterns of crop yield for 18 different crops, estimating the differences between actual yield and the climatic potential yield (as defined by a comparative statistical analysis of other regions with similar climatic conditions). A resulting 'yield gap' – the difference between actual yield and the climatic potential – is calculated for all crops.

With these estimates of the climatic yield gap, we can effectively remove the influence of climate on crop yields and highlight the additional yield that could be obtained through an alteration of other drivers, like agricultural management. The yield gap maps demonstrate that there is a considerable spread in yields across the world, even among places that have a similar number of GDDs and level of soil moisture availability.

According to this analysis, approximately 50% more maize, nearly 40% more rice, 20% more soybean and 60% more wheat could be produced if the top 95% of the crops' harvested areas met their current climatic potential. However, it is not clear from this analysis whether all of the regions will be able to undergo the changes to their management practices and obtain the varieties necessary to achieve these yields. For some regions, this would necessitate overcoming major socio-economic and political hurdles that have kept them from already achieving higher yields. In addition, it is not clear yet whether achieving such gains in yields will be possible without significantly damaging other ecosystem goods and services that society is dependent on.

On the other hand, our estimates of potential yield, and the resulting 'yield gap', are not setting firm limits on the 'maximum' yield that will ever be obtainable. Rather, we simply examine the maximum climatic-potential yields currently being achieved

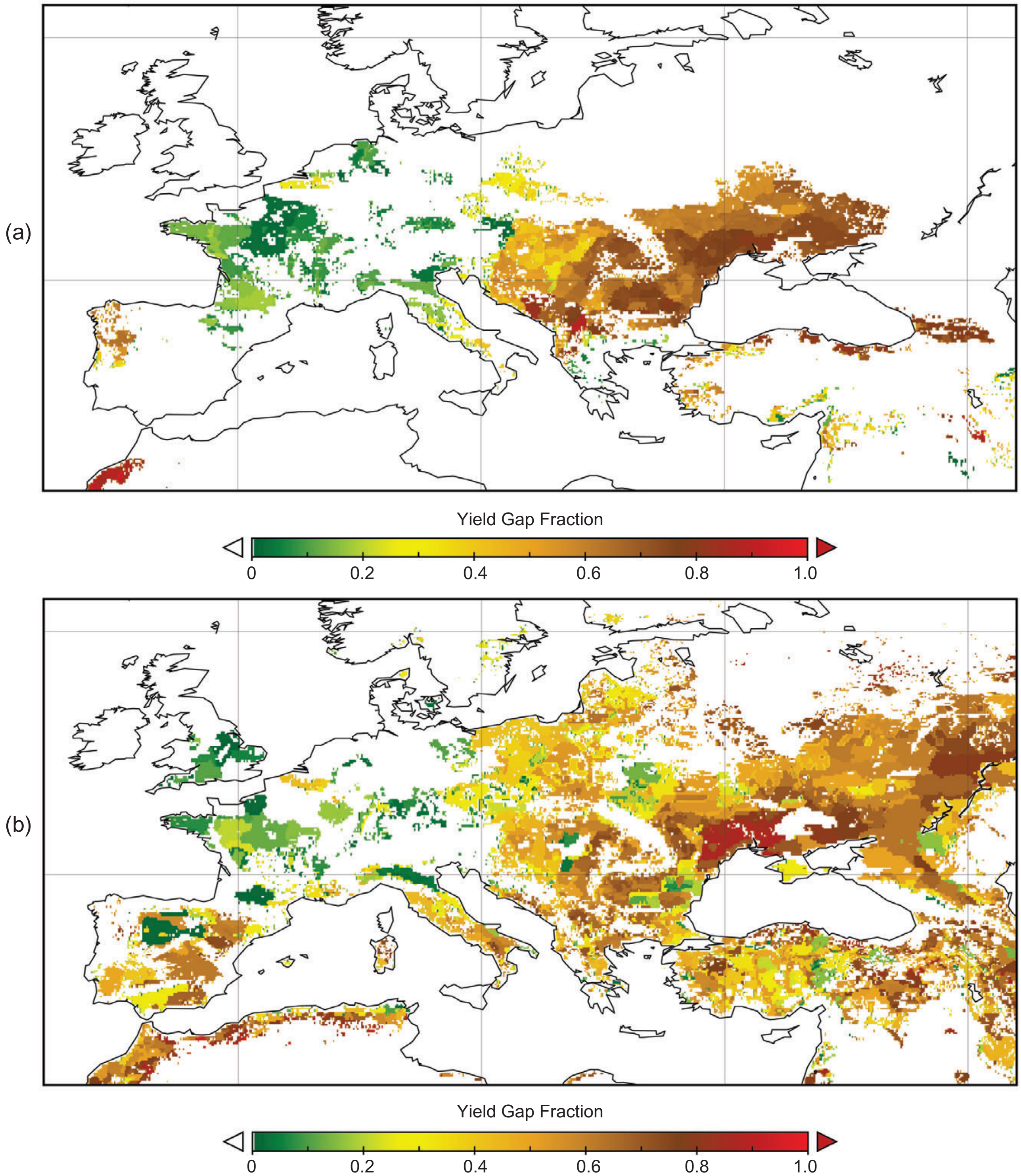

Figure 7 Yield gap fraction detail on a 5′ grid with an equirectangular projection for (a) wheat and (b) maize in eastern and western Europe.

with best management practices and currently utilized crop varieties in the world around the year 2000. Further advances in seed genetics, biotechnology, agronomic management techniques and other agricultural technology may further boost maximum yields far beyond what we see today. Instead, our analysis considers *today's* maximum achievable yields, for each climate zone, and illustrates where we can potentially increase yields *today* – without further advances in crop genetics or biotechnology – by changing agricultural practices that are already in place around the world.

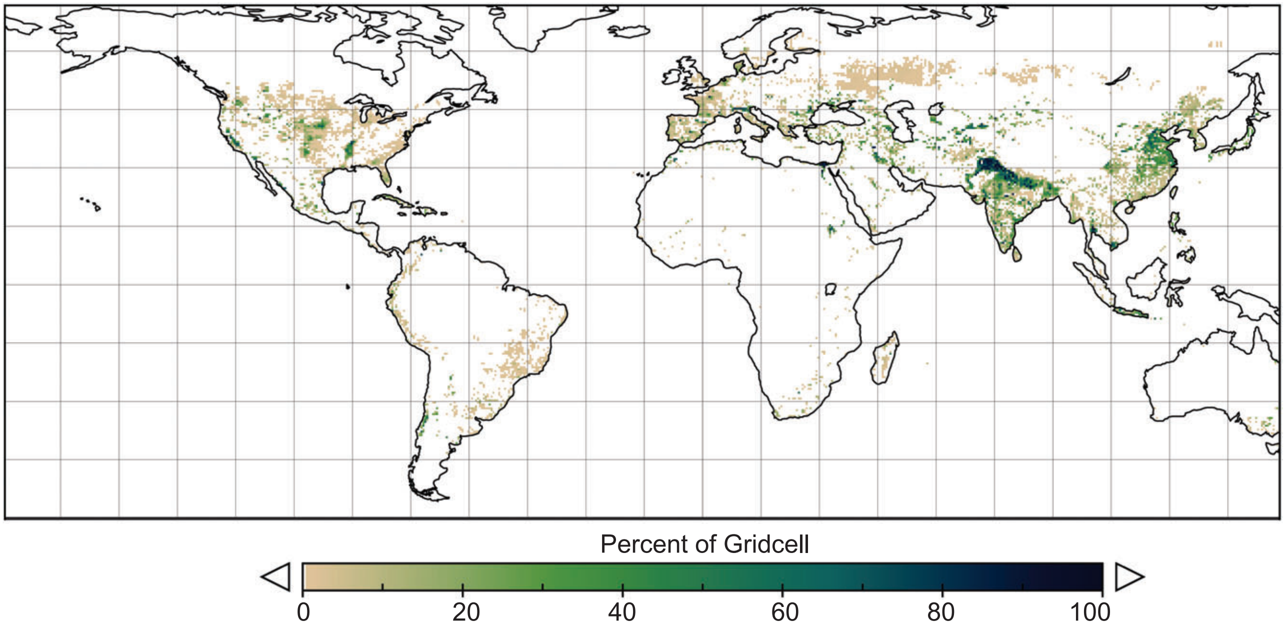

Figure 8 Percentage of grid cells equipped for irrigation on a 5′ grid with an equirectangular projection (data from Siebert *et al.* 2007).

With continued increases in the demand for agricultural products – for food, feed and biofuels – we face a pressing need to boost agricultural production. These production gains will require some combination of: (1) increasing yields on existing croplands (i.e. closing the yield gaps); (2) expanding agricultural lands into natural ecosystems, often at the loss of critical ecosystems and biodiversity hotspots; or (3) reallocating current agricultural production to more productive uses (e.g. shifting grains from animal feed to human consumable food, with vast improvements in overall system efficiency). Each of these options has potential benefits and disadvantages, as well as significant associated challenges.

As agriculture is currently practised, increasing yields on existing lands can lead to soil erosion, and intensive water application on irrigated lands can result in ground and surface water salinization (Tilman, 1999). Many of the impacts of agricultural expansion are similar to those of agricultural intensification, but also include other concerns such as the loss of biodiversity due to habitat destruction (Tilman *et al.*, 2001), as well as changes in local, regional and global climate as a result of land-surface feedbacks (Bonan, 1997; Stohlgren *et al.*, 1998; Costa & Foley, 2000; Fu, 2003).

In addition, intensive agriculture usually involves high levels of chemical input that are known to disrupt water and air quality, amongst other ecosystem services (Cassman, 1999; Tilman *et al.*, 2002; Foley *et al.*, 2005). For example, many coastal regions have hypoxic water due to agricultural fertilizer run-off (Diaz & Rosenberg, 2008). Some of the best-known cases are the hypoxia of the Gulf of Mexico that stems from the agriculture surrounding the Mississippi River, and that around the Kattegat resulting from northern Europe's intensive agriculture. The low dissolved oxygen content of these water bodies has reduced their fishery output – an important natural resource for those regions.

While crop productivity declined in the Former Soviet Union following its collapse in the early 1990s, the decrease in fertilizer use that precipitated the decrease in yields benefited many coastal ecosystems, and the communities that depend on them. For example, hypoxia in the Black Sea has largely disappeared (Mee, 2006). Such trade-offs are important to consider when societies decide how to manage their resources. This is especially true in light of the concern that Matson *et al.* (1997) raise: that intensively managed agricultural lands may eventually become degraded and less productive.

These common consequences of conventional intensive agriculture highlight the importance of continued research into alternative high-yielding farming practices that are not necessarily destructive to ecosystem goods and services, and in turn, to the societies that rely on them.

Of course, the gain in all of these scenarios is an increase in crop production, which, if equitably distributed, could alleviate food shortages. Another challenge will be to deal with the pressures that changing diets are placing on food supplies. While grain-fed meat consumption is already high in developed countries, it is projected to increase dramatically in coming decades in developing countries, particularly in Asia, in response to the growing incomes and fast-paced urbanization that is taking place in these regions (Rosegrant *et al.*, 2001). Much of this demand will be met through an increase in meat production in the developing world, which will increase demand for feed grains (de Haan *et al.*, 2001). Delgado *et al.* (1999) project the demand for feed grain in developing countries will increase from 1997's baseline of 235 million tons per year to 432 million tons per year in 2020. Such shifts in the dietary patterns of some populations in the developing world may compromise the food security of the less wealthy (de Haan *et al*., 2001).

Whether the yield gaps demonstrated in this paper can actually be 'closed', and closed in a sustainable manner for both human and ecological systems, remains in question. The challenge of charting a path in which high-yielding agriculture is widespread and less detrimental to the ecosystem goods and services at large continues.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Appendix S1 Global crop yields.
Appendix S2 Climatic potential crop yield values.
Appendix S3 Crop yield gap fraction values.
Appendix S4 Calculation of the crop soil moisture index, as a ratio of actual evapotranspiration to potential evapotranspiration (AET/PET).

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R.L., M.J., J.A. and N.R. conceived the ideas. C.M., N.R. and C.B. collected and generated the data. R.L., M.J. and C.J.K. analysed the data. R.L. and J.A.F. led the writing. R.L., M.J., J.A.F., C.B., C.J.K., C.M. and N.R. contributed to the writing and revisions.

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