LETTER

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Closing yield gaps through nutrient and water management

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In the coming decades, a crucial challenge for humanity will be meeting future food demands without undermining further the integrity of the Earth's environmental systems[1–6]. Agricultural systems are already major forces of global environmental degradation[4,7], but population growth and increasing consumption of calorie- and meat-intensive diets are expected to roughly double human food demand by 2050 (ref. 3). Responding to these pressures, there is increasing focus on 'sustainable intensification' as a means to increase yields on underperforming landscapes while simultaneously decreasing the environmental impacts of agricultural systems[2–4,8–11]. However, it is unclear what such efforts might entail for the future of global agricultural landscapes. Here we present a global-scale assessment of intensification prospects from closing 'yield gaps' (differences between observed yields and those attainable in a given region), the spatial patterns of agricultural management practices and yield limitation, and the management changes that may be necessary to achieve increased yields. We find that global yield variability is heavily controlled by fertilizer use, irrigation and climate. Large production increases (45% to 70% for most crops) are possible from closing yield gaps to 100% of attainable yields, and the changes to management practices that are needed to close yield gaps vary considerably by region and current intensity. Furthermore, we find that there are large opportunities to reduce the environmental impact of agriculture by eliminating nutrient overuse, while still allowing an approximately 30% increase in production of major cereals (maize, wheat and rice). Meeting the food security and sustainability challenges of the coming decades is possible, but will require considerable changes in nutrient and water management.

Opportunities for agricultural intensification were analysed for seventeen major crops (which covered approximately 76% of global harvested cropland area between 1997 and 2003 (Food and Agriculture Organization of the United Nations)). Yield gaps (Fig. 1) were estimated by comparing landscape-level observed yields[12] to 'attainable yields', determined by identifying high-yielding areas within zones of similar climate. As empirical estimates, attainable yields are more conservative than absolute biophysical 'potential yields'[13], but they are probably achievable using current technology and management techniques.

Considerable yield-improvement opportunities exist relative to current attainable yield ceilings, with opportunities differing dramatically by crop and geography (regional and country-specific data for all seventeen crops are summarized in the Supplementary Information). Globally, we find that closing yield gaps to 100% of attainable yields could increase worldwide crop production by 45% to 70% for most major crops (with 64%, 71% and 47% increases for maize, wheat and rice, respectively). Eastern Europe and Sub-Saharan Africa show considerable 'low-hanging' intensification opportunities for major cereals (Fig. 2); these areas could have large production gains if yields were increased to only 50% of attainable yields. East and South Asia also have substantial intensification opportunities owing to their vast agricultural lands and the geographic variability in their yields and yield gaps.

Assessing opportunities for more sustainable intensification requires an understanding of the factors driving yield variation across the world. Fundamentally, yield gaps are caused by deficiencies in the biophysical crop growth environment that are not addressed by agricultural management practices. Here we explicitly examined key biophysical drivers of crop yield by using global, crop-specific irrigation data[14] and by developing a new global, crop-specific data set of nitrogen (N), phosphate (P_2O_5) and potash (K_2O) fertilizer application rates. We find extensive geographic variation in these management practices, with high fertilizer application rates concentrated in high-income and some rapidly developing countries (Fig. 3a and Supplementary Fig. 1). Likewise, irrigated areas[14] are heavily concentrated in South Asia, East Asia and parts of the United States (Fig. 3b).

Using input–yield crop models, we found that the spatial patterns of climate, fertilizer application and irrigated area explain 60% to 80% of global-yield variability for most major crops (Supplementary Information and Supplementary Table 1). Yields of some crops (for example, sorghum, millet and groundnut) were primarily controlled by climate, whereas others (for example, barley, sugar beet and oil palm) showed strong management responses. Surprisingly, model residuals showed little sensitivity to soil and slope parameters (Supplementary Information and Supplementary Fig. 2), suggesting that such relationships are obscured on the landscape scale with existing data sets.

The factors that primarily limit increasing crop yields to within 75% of their attainable yields (Fig. 4, Supplementary Fig. 3) vary by crop and region. For example, Eastern Europe and West Africa stand out as hotspots of nutrient limitation for maize, whereas Eastern Europe seems to experience nutrient limitation for wheat. Co-limitation of nutrients and water is observed across East Africa and Western India for maize, portions of the US Great Plains and the

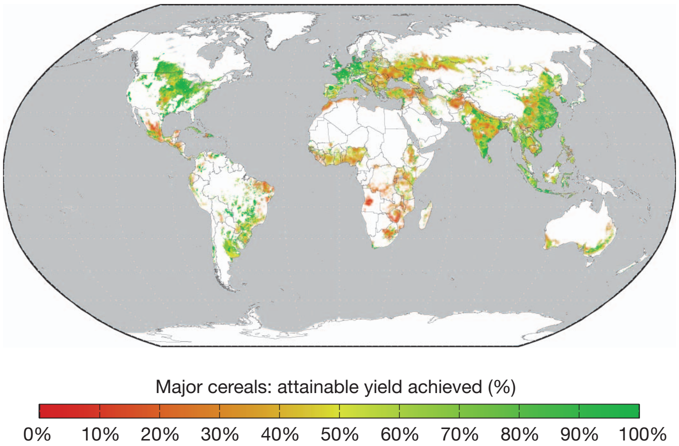

Figure 1 | Average yield gaps for maize, wheat and rice. These were measured as a percentage of the attainable yield achieved circa the year 2000. Yield gap in each grid cell is calculated as an area-weighted average across the crops and is displayed on the top 98% of growing area.

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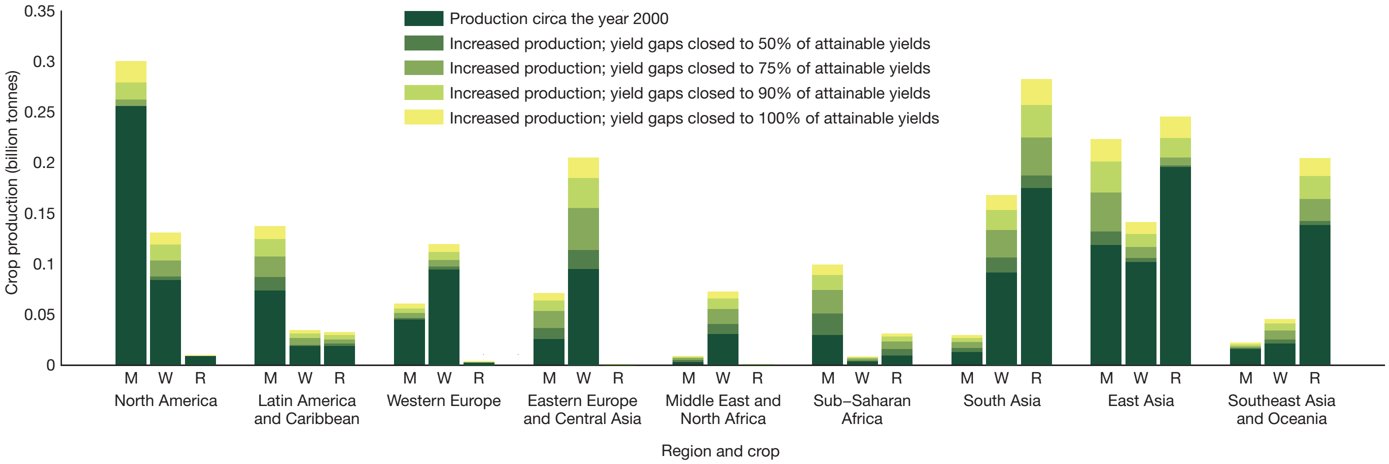

Figure 2 | Global production increases for maize, wheat and rice from closing yield gaps to 50%, 75%, 90% and 100% of attainable yields. The greatest opportunities for increases in absolute production (from closing yield gaps to 100% of estimated attainable yields) are wheat (W) in Eastern Europe and Central Asia, rice (R) in South Asia and maize (M) in East Asia. Absolute production increases for individual crops in Sub-Saharan Africa are smaller owing to lower attainable yields and diverse cropping systems (that is, less area devoted to any one crop). The region could still achieve large production increases in cassava, maize and sugarcane.

Mediterranean Basin for wheat, and in Southeast Asia for rice. We note that the management practices that limit yield increases depend on the degree of yield-gap closure desired (Supplementary Fig. 4). For example, closing maize yield gaps to 50% of attainable yields (approximately 2.3 tonnes per hectare) in Sub-Saharan Africa primarily requires addressing nutrient deficiencies (Supplementary Fig. 4a), but closing yield gaps to 75% of attainable yields (approximately 3.5 tonnes per hectare) requires increases in both irrigated area and nutrient application over most of the region (Fig. 4a).

We examined potential changes in irrigated area and nutrient application that are needed to close yield gaps of maize, wheat and rice to within 75% attainable yields (a 29% global production increase) using our input–yield models. On the landscape scale, yield gaps in co-limited regions can be closed through a range of irrigated-area and nutrient-intensity combinations (see Supplementary Fig. 5). For example, 73% of these underachieving areas could close yield gaps by solely focusing on nutrient inputs (with 18%, 16% and 35% increases in N, P_2O_5 and K_2O application relative to baseline global consumption, respectively), whereas only 16% of underachieving areas could close yield gaps by solely increasing irrigation. Jointly increasing irrigated area and nutrient application could close yield gaps on all underachieving areas (with 30%, 27% and 54% increases in N, P_2O_5 and K_2O application, respectively, and a 25% increase in irrigated hectares; Fig. 5a, b).

To minimize the environmental impacts of intensification, increased irrigation and nutrient application to close crop yield gaps should be complemented by efforts to decrease overuse of crop inputs wherever possible[15–18]; combined, these efforts could increase total food production while decreasing the overall global use of water and nutrients. For example, we estimate that by addressing imbalances and inefficiencies, nitrogen- and phosphate-fertilizer application on maize, wheat and rice could decrease globally by 11 million tonnes of nitrogen (28%) and 5 million tonnes of phosphate (38%) without impacting current yields (Supplementary Fig. 6). Nutrient overuse on these crops is particularly dramatic in China, confirming field-scale results[15]. To close yield gaps to 75% of attainable yields while also eliminating input overuse (under joint nutrient and irrigation intervention), we project that smaller net changes in nutrient inputs would be required: 9%, −2% and 34% changes in N, P_2O_5 and K_2O application (Fig. 5c and Supplementary Fig. 7). Notably, it would be possible to close global yield gaps on major cereals to within 75% of attainable yields with fairly minimal changes to total worldwide nitrogen and phosphate use by coupling targeted intensification with efforts to reduce nutrient imbalances and inefficiencies. Geographically optimizing input intensity and increasing field-scale efficiencies (beyond the average efficiencies implicit in our input–yield models) could improve production further relative to inputs.

Closing yield gaps may not always be desirable or practical in the short term, given marginal returns for additional inputs, regional

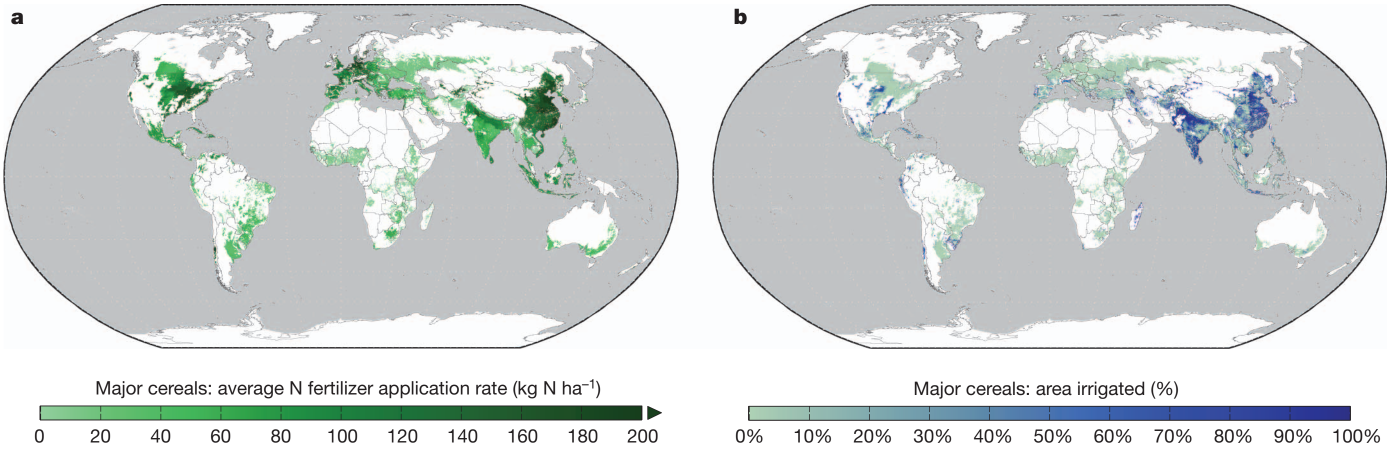

Figure 3 | Management intensity of nitrogen fertilizer and irrigated area[14] varies widely across the world's croplands. **a**, **b**, Fertilizer (**a**) and irrigation (**b**) values are area-weighted averages across major cereals.

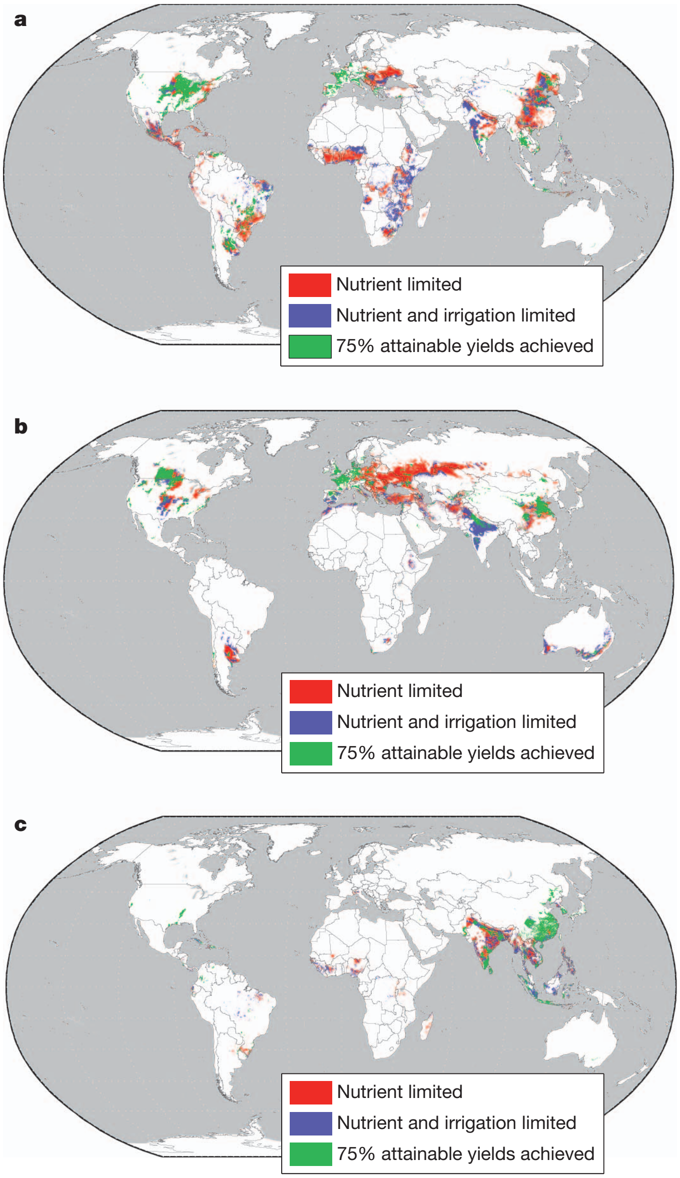

Figure 4 | Management factors limiting yield-gap closure to 75% of attainable yields for maize, wheat and rice. a, b, c Yield-limiting management factors for maize (**a**), wheat (**b**) and rice (**c**) were calculated using the suite of input–yield models, comparing current input intensity against estimated required levels to close yield gaps.

land-management policies, limits on sustainable water resources and socio-economic constraints (for example, access to capital, infrastructure, institutions and political stability). However, use of precision agriculture techniques, conservation tillage, high-yielding hybrids, increased plant populations and multifunctional landscape management can help to mitigate negative environmental impacts of intensive agriculture[19–21]. Additionally, use of organic fertilizers (omitted in this analysis owing to data limitations) are essential for improving soil carbon, enhancing soil biota and increasing water-holding capacity[22]. Social triggers of intensification will differ across regions; for example, because of development interventions by governments or NGOs, market-driven incentives for farmer investment, and land scarcity in regions not fully connected to global markets[23].

Changes to agricultural management to close yield gaps should be considered in the context of climate change, which is expected to substantially impact yields[24,25] and induce management adaptations[26]. Specifically, a major concern is how changes in water availability may conflict with projected irrigation requirements for closing yield gaps.

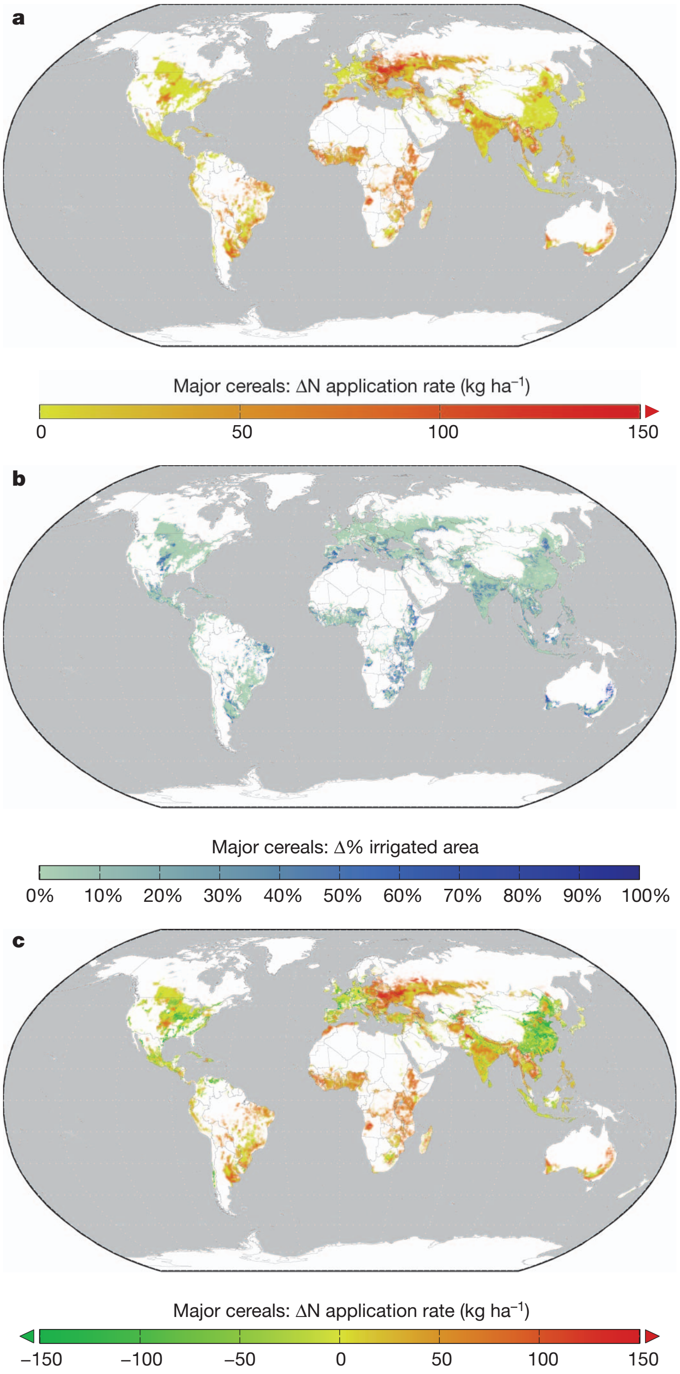

Figure 5 | Closing yield gaps through changes in agricultural management. a, **b**, Projected increases in nitrogen application rates (**a**) and irrigated areas (**b**) necessary to close maize, wheat and rice yield gaps to 75% of attainable yields. **c**, Projected net changes in nitrogen application rates when closing yield gaps and eliminating input imbalances and inefficiencies.

The fertilizer data set, yield gap estimates and yield models presented here could be used widely to assess intensification opportunities and the environmental impacts of changing agricultural systems. However, these data and analyses are not without limitations (full discussion in Supplementary Information). Most importantly, the analyses rely on agricultural management, yield and climate data from a variety of different sources and on different scales. Overall, these results are most useful across regional and global scales, leaving fine-scale and temporal details obscured (for example, intra- and inter-annual variation in climate and yield creates particular uncertainty about irrigation requirements). Moreover, although our models confirm the importance of climate, fertilizers and irrigation in determining contemporary patterns of global cropland productivity, we do not discount the importance of additional biophysical characteristics (including soil characteristics, see Supplementary Information) and management practices (including crop rotation patterns, organic nutrient inputs, micronutrients, improved seed quality, conservation tillage and pest management). Incorporating these factors into the analytical framework could improve the accuracy and utility of the analyses. Additional research on cropland intensification must also assess the opportunities and environmental tradeoffs for increasing cropping intensity and decreasing pre- and post-harvest crop losses.

The future of agriculture faces two great challenges: substantial increases in food demand must be met while decreasing agriculture's global environmental footprint. Closing yield gaps and increasing resource efficiency are necessary strategies towards meeting this challenge, but they must be combined with efforts to halt agricultural expansion, reduce food waste and promote sensible diets, and produce advanced crop varieties[1,4]. This analysis emphasizes the crucial role of nutrient and water management in pathways towards sustainable intensification, and provides a starting point for a more comprehensive discussion of intensification opportunities and challenges. Context-dependent policies and agricultural development programs must address drivers of yield limitation while encouraging management practices that improve tradeoffs between production and environmental impacts.

METHODS SUMMARY

Yield gaps were quantified by comparing existing yields to climate-specific attainable yields. Our approach refines previous estimates[27,28] by excluding climate outliers and using crop-specific, equal-area climate zones.

Fertilizer application rate and consumption data were compiled for nations and subnational units across the globe (Supplementary Table 2). Application rates for crop–country combinations missing data were estimated as described in the Supplementary Information. Crop- and crop-group-specific application rates were then distributed across detailed maps of crop[12] and pasture[29] areas, and rates were harmonized with subnational and national nutrient consumption data.

Fertilizer and irrigation data were used to parameterize nutrient response curves and rainfed maximum yields, using nonlinear regression analyses within each climate zone. Using these relationships, we estimated changes in inputs necessary to close yield gaps, as well as decreases in inputs possible from addressing inefficiencies and imbalances.

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Supplementary Information is available in the online version of the paper.

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