Scope for improved eco-efficiency varies among diverse cropping systems

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Global food security requires eco-efficient agriculture to produce the required food and fiber products concomitant with ecologically efficient use of resources. This eco-efficiency concept is used to diagnose the state of agricultural production in China (irrigated wheat–maize double-cropping systems), Zimbabwe (rainfed maize systems), and Australia (rainfed wheat systems). More than 3,000 surveyed crop yields in these three countries were compared against simulated grain yields at farmer-specified levels of nitrogen (N) input. Many Australian commercial wheat farmers are both close to existing production frontiers and gain little prospective return from increasing their N input. Significant losses of N from their systems, either as nitrous oxide emissions or as nitrate leached from the soil profile, are infrequent and at low intensities relative to their level of grain production. These Australian farmers operate close to eco-efficient frontiers in regard to N, and so innovations in technologies and practices are essential to increasing their production without added economic or environmental risks. In contrast, many Chinese farmers can reduce N input without sacrificing production through more efficient use of their fertilizer input. In fact, there are real prospects for the double-cropping systems on the North China Plain to achieve both production increases and reduced environmental risks. Zimbabwean farmers have the opportunity for significant production increases by both improving their technical efficiency and increasing their level of input; however, doing so will require improved management expertise and greater access to institutional support for addressing the higher risks. This paper shows that pathways for achieving improved eco-efficiency will differ among diverse cropping systems.

APSIM | nitrogen fertilizer | potential yield | yield gap | greenhouse gas

Food security is an international challenge given concerns over rising population, world food stocks, the food or biofuel debate, increasing water scarcity, declining natural resource status, climate change, and increasing energy costs. Livelihoods and prosperity are increasing in some parts of the world, driving increased dietary diversification and higher per capita fiber and energy consumption. Conversely, other parts of the world find it harder to meet basic food and energy requirements. Looking forward, international agriculture must produce >70% more food by 2050 to meet the projected increases in population and consumption (1, 2). International imperatives include increasing the production of major food crops to keep pace with projected increases in food demand while also improving the livelihoods of smallholder farming communities, protecting the environment, and mitigating agricultural greenhouse gas emissions. The question is whether agriculture can create the eco-efficiencies in resource use to meet these production and sustainability challenges (1, 3–5).

The capacity for agricultural systems globally to further intensify, to realize higher yields and increased production, is a critical assumption in current assurances that the world is food-secure into the future. The observable yield gap between current production per hectare and estimates of potential production at both global and regional scales (6, 7) is often regarded as a virtual food cache within reach of the world's population, accessible when required. The global response of record cereal production after the 2008 and 2010 food crises, and consequent grain price hikes (8), are indicators that increased food supply can result from demand and price signals. However, it may be a leap of faith to assume that yield gaps relative to potential estimates can be fully marshaled on call to meet increases in food demand.

There have been many quantitative analyses of yield gaps (3, 5, 7, 9, 10), with an emerging consensus in their determination. As an indicator of the prospects for potential productivity increases, a potential yield gap can be established between actual farm yield (Y) and potential yield (Y_p) (Fig. 1), quantified as the production attained using optimal inputs, the best agronomy, and an absence of limiting stresses. Generally, Y_p is determined using a simulation model (10). Closing this yield gap is not simply a matter of improving the efficiency of agronomic and farm operations (technical efficiency) to ensure that crop yields are fully realized. The reality is that many crops are limited by water availability, which is certainly the case for rainfed crops and often for irrigation systems with limits to water supply, and so there is a water-limited yield (Y_w) potential. The economically optimal yield (Y_o) usually will be even lower, owing to diminishing returns to increasing inputs, and the attainable yield (Y_a) may be lower still, as most farmers invest less than the economic optimum because of limited resource availability and perceptions of risk.

The foregoing concepts are illustrated in Fig. 1 using an output-input response function representing a production frontier of attainable yields relative to a level of inputs, the investment in which is determined by economic, environmental, and social considerations (4). Here the attainable yield gap is the difference between Y and the corresponding Y_a, determined for the same level of inputs and assuming no other limiting stresses.

In the consideration of yield gaps, three questions are addressed. First, how close are farmers to the production frontier of attainable yields set by their current levels of input investment? Second, based on this assessment, what crop intensification pathways are likely to lead to increased food production, and how will they differ between systems? Finally, can such intensification pathways encompass environmental benefits? For some farmers in

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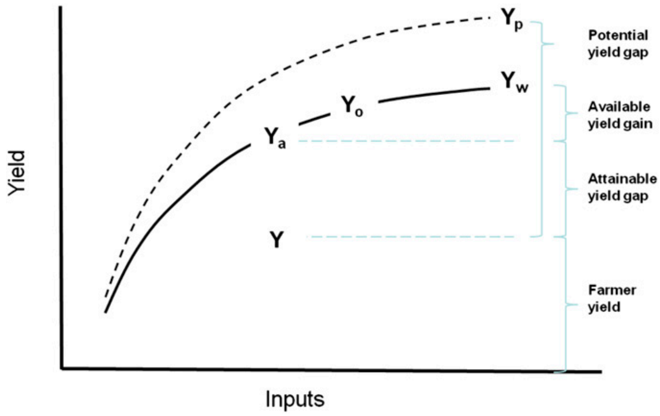

Fig. 1. Yield-input production functions using current best technologies under rainfed (solid line) and irrigated systems (dashed line).

some regions, improving operations and agronomic management may be the logical path to production increases. For other farmers, such improvements already have been realized, and production increases must come from higher input investment and possible exposure to greater investment or environmental risks. Clearly, a legitimate and proven pathway to agricultural productivity increases is through research and development leading to new technologies and hence redrawn frontiers of attainable yields (4). Viewing yield gaps as a ready source of future food supply without a concomitant assessment of the realistic and locally specific pathways to achieving yield gains does not tell the whole story.

The response in grain yield of crops to the application of nitrogen (N) fertilizer is the focus of the present study. N fertilizer is produced from natural gas and is high in embedded energy and global warming potential. As a nonrenewable resource, it is subject to energy-market related fluctuations in supply and price. The application of N fertilizer to crops generally results in higher yields, increased protein in grain, and increased return of stubble cover and maintenance of soil organic matter. However, N unused by crops can be lost as emissions of potent greenhouse gases, including nitrous oxide (N_2O), or from the root zone, leading to acidification in soils and nitrate contamination of water resources (11). Consequently, improved management of N fertilizers, leading to zero or low-intensity N emissions, serves as a key indicator of improved production and environmental performance of cropping systems (12–15).

Assessing the prospects for ecological intensification and increased production requires marrying available data on crop performance with reasonable estimates of attainable and potential yields. In this study, we accessed data on grain yields from 3,041 crops from single fields, along with associated site characteristics and management practices, for farms in China (irrigated wheat–maize double-cropping systems), Zimbabwe (rainfed maize systems), and Australia (rainfed wheat systems) (Table 1). Y_a and Y_p values for these crops were simulated using the Agricultural Production Systems Simulator (APSIM) (16), which has been widely tested in the three case study systems (17–19) and was specifically parameterized for this study (*SI Text*). Our objective was to diagnose the state of agricultural production in these contrasting agricultural systems and suggest appropriate pathways for improving eco-efficiencies and closing yield gaps.

Results and Discussion

Benchmarked Production. In Fig. 2, the performance of wheat–maize double crops grown on China's Hebei Plain is benchmarked against a simulated production frontier. The striking aspect of this representation is the number of farmers who applied N fertilizer at rates exceeding the recommended annual rate of 500 kg N/ha, with some fields receiving more than 1,000 kg N/ha. Overfertilization of crops on the North China Plain is a well-recognized significant environmental concern (20). Despite the very high N rates in some of the surveyed crops, most crops clearly underperformed relative to both the simulated production frontier and the researcher-designed, farmer-implemented demonstration plots located within the six counties in Hebei Province (Fig. 2). At fertilizer rates below recommended levels, some wheat–maize double crops performed close to the frontier and a few performed better than the frontier, likely because of greater actual presowing soil mineral N availability compared with the value used in the simulations.

Although conceptually, the performance of farmers in a common cropping system can be mapped against an attainable production frontier, it is not possible to reproduce this simple representation for crops produced under the rainfed systems in Australia and Zimbabwe. The wheat–maize double-cropping system in China can be considered relatively homogeneous as a fully irrigated, high-input system in a region that generally conforms to a standard double-crop sequence each season. In this case, it is reasonable to compare neighboring farms with a common production frontier. In contrast, rainfed cropping systems and fields are far more heterogeneous, driven by spatial variability in both rainfall and soil characteristics and by temporal variability in crop sequences and their consequent carry-over impacts (21, 22). Whereas each crop can be compared with a production frontier for its own situation, neighboring crops can have very different frontiers and estimates of Y_a and Y_w. One approach to assessing crop performance relative to an efficiency frontier is to normalize yields and relative inputs to enable such representation (13); another is to simply report the technical efficiency (Y/Y_a) for each crop (7).

Improving Technical Efficiency. Fig. 3 iillustrates the technical efficiency (Y/Y_a) of cropping systems in Australia, China, and Zimbabwe. The Chinese data shown in Fig. 3*A* (transformed from Fig.

Table 1. **Description of the datasets from Australia, China, and Zimbabwe, including observed and simulated yields**

	Australia, 2004–2011	China, 2004–2005			Zimbabwe, 2003–2006	
Parameter	Wheat	Wheat	Maize	Wheat–maize	Maize	Maize + 17 kg N/ha
No. of crops	849	351	351	351	745	745
Average rainfall, mm	182	125	397	522	445	445
CV rainfall, %	48	55	41	33	32	32
Average N rate, kg/ha	27	260	224	484	0	17
CV N rate, %	28	49	125	65	—	—
Average Y, kg/ha	2,270	6,541	7,332	13,874	1,023	1,520
CV Y, %	65	12	15	12	87	79
Average Y_a, kg/ha	2,211	8,601	12,432	21,033	1,823	2,458
Average Y_w, kg/ha	2,532	10,304	12,490	22,794	2,973	2,973
Average Y_p, kg/ha	5,738	10,304	12,490	22,794	7,176	7,176

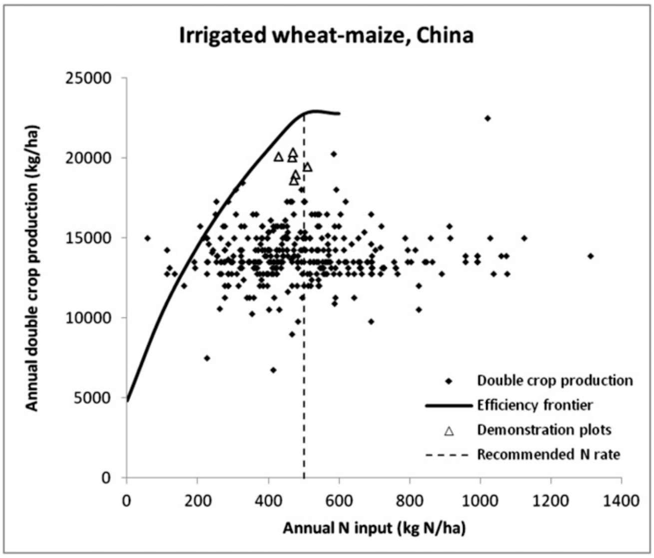

Fig. 2. Annual production (kg/ha) and fertilizer rates (kg N/ha) of irrigated wheat–maize double crops from 351 farmer fields and 6 demonstration plots in Hebei Province over the 2004–2005 season. The solid curve is the simulated production response function, and the dotted line represents the recommended N application rate of 500 kg N·ha^{-1}·y^{-1}.

2) emphasize the underperformance in this system, especially for those systems that targeted the maximum attainable grain production of 23,000 kg/ha. Likewise, the majority of rainfed maize crops in Zimbabwe produced grain yields significantly below their attainable yields, whether grown using the predominant farmer practice of no added inorganic fertilizer or when a small fertilizer dose (17 kg N·ha^{-1}) was applied (Fig. 3*B*). These data demonstrate generally higher grain yields from a small fertilizer dose, as has been reported by Twomlow et al. (23). Similar to the China dataset, some crops yielded greater than the simulated yield, likely owing to higher water and/or N resource availability compared with that used in the simulations.

In contrast to the China and Zimbabwe datasets, actual rainfed wheat grain yields in Australia were clustered around the 1:1 line between Y and Y_a (Fig. 3*C*). Many crops yielded close to their attainable grain yield. This result reflects the situation in Australia, where APSIM is expected to closely simulate commercial crop yields (17) and in fact provides farmers with a reliable yield forecasting and crop management system (24). A proportion of crops demonstrated sizeable underpredictions and overpredictions, with some producing yields greater than what APSIM simulated, as could be expected given the available climate, soil, and fertilizer resources. The larger underpredictions by APSIM can only be attributed to misspecification of the system (eg, soil, climate) or errors in the Yield Prophet database. Overpredictions by APSIM may have the same attribution, but for the purpose of this study, they are included in the assessment of technical efficiency.

Converting Y/Y_a into a probability of exceedence graph (Fig. 4*A*), an Australian rainfed wheat crop from this database has a 71% probability of exceeding a technical efficiency of 0.8 (within 20% of the production frontier) and an 88% probability of exceeding a technical efficiency of 0.5. These findings affirm the assertion that many Australian farmers are currently operating close to their attainable production frontiers (17). Efficient performance might reflect that farmer subscribers to an advanced system such as Yield Prophet are likely elite farmers whose performance is superior to that of the normal farmer population. Regardless, this survey of more than 800 crops grown over multiple seasons and locations strongly suggests that many Australian farmers perform well in their agronomy and are driven by economic realities to be as efficient as possible in crop production.

Of the irrigated wheat–maize double crops grown on the Hebei Plain, only 12% exceeded a technical efficiency of 0.8, but 97% of the farms had a technical efficiency >0.5 (Fig. 4*A*). In this survey, the Chinese farmers achieved a reasonable platform in technical efficiency, reflecting both a baseline in the application of available technologies and the advantages of irrigated systems. However, farmer-implemented on-farm demonstrations achieved an average technical efficiency of 0.85, demonstrating what can be realistically achieved when identified constraints are addressed (12).

The situation in Zimbabwe is different; 28% of crops had a technical efficiency >0.8, and only 45% had a technical efficiency >0.5 (Fig. 4*A*). The majority of these smallholder maize crops produced less than half of what could be expected, even considering the very low yields and investment levels in fertilizer application. Alongside the call for higher investments in soil fertility and fertilizer use in sub-Saharan Africa (23, 25) is a basic prerequisite to improve the agronomic practices and technical skills of African farmers (26).

Increased Input Investment. A second question addresses the crop intensification pathways that can lead to increased food production available to farmers. Improving technical efficiency is prospective for Chinese and Zimbabwean smallholder farmers, and maybe less so for Australian commercial farmers. The other option is to increase the farmers' investment in inputs—in the case of the present study, increase N fertilizer—and so potentially move up and along the attainable production frontier toward Y_o and Y_w (Fig. 1). The reasons why farmers do not take this action are well rationalized around issues of lack of knowledge, concerns about perceived and realized risks, inaccessibility of input services and credit, and/or inconsistency with personal aspirations (27).

The available yield gain percentage was used to estimate the prospects for increased production by increasing rates of N fertilizer application on surveyed farm crops (Fig. 4*B*). For the surveyed wheat–maize double crops grown on the Hebei Plain, 19% of crops could expect >20% higher grain production from an increased investment in N fertilizer (500 kg N·ha^{-1}·y^{-1}); 57% of the farmers could expect zero benefit or were already investing at or beyond this recommended rate. On the North China Plain, the imperative is plainly to lower fertilizer application rates without affecting food production (20).

In Australia, 22% of the surveyed wheat crops could expect >20% higher yields from an increased investment in N fertilizer (at a rate required to achieve Y_w); 50% of the farmers realized no benefit from applying extra fertilizer to these crops (Fig. 4*B*). It seems that the majority of (elite) Australian wheat farmers are already operating well along the attainable production frontier (in terms of N nutrition) and so have little room to increase their production via this route.

As expected, the situation is different in Zimbabwe. Of the surveyed maize crops grown using farmer practice (i.e., no top dressing with N fertilizer), 52% could expect >40% higher yields from an increased investment in N fertilizer (at a rate required to achieve Y_w), and 71% of the farmers could expect a >20% increase in yield (Fig. 4*B*). Thus, there are real gains to be made from moving these African farmers further along the fertilizer investment curve (23).

Environmental Consequences. A consequence of intensified cropping systems is the increased use of inputs such as N fertilizer and the consequent N losses from the system, which can lead to environmental degradation. For the Australian case study, these losses are quantified as probability distributions of simulated annual N_2O emissions and leached nitrate expressed relative to grain yield production as measures of global warming potential intensity

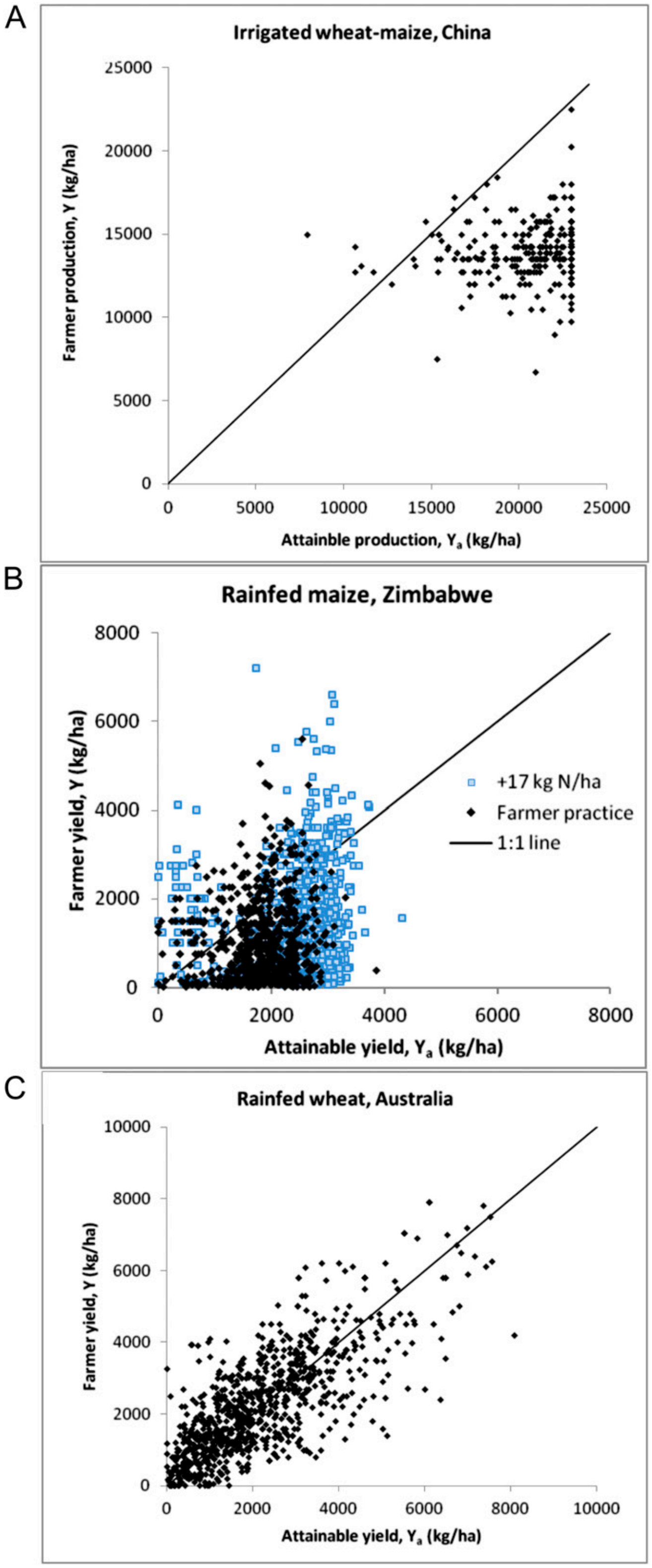

Fig. 3. Actual crop production (kg/ha) and corresponding simulated production (kg/ha) of irrigated wheat–maize double crops from 351 farmer fields in China over the 2004–2005 season (*A*), rainfed maize crops from 745 farmer fields (paired plots of farmer practice and plus 17 kg N/ha) in Zimbabwe over the 2003–2006 seasons (*B*), and rainfed wheat crops from 849 farmer fields in Australia over the 2004–2011 seasons (*C*).

(kg $CO_2e{\cdot}Mg^{-1}$ grain) and N leaching intensity (kg $N{\cdot}Mg^{-1}$ grain) (Fig. 5). Across all of the crops, regions, and conditions studied, 13% of cases were simulated to have released no N_2O, and 95% of emissions had a global warming potential intensity <200 kg $CO_2e{\cdot}Mg^{-1}$ grain, a level below which intensive crop production has been deemed reasonable (15). The average global warming potential intensity across the 849 crops studied was 45 kg $CO_2e{\cdot}Mg^{-1}$ grain. Only 17% of simulations predicted the occurrence of nitrate leaching, with average and maximum leaching losses estimated at 1.8 and 91 kg $N{\cdot}ha^{-1}$, respectively. These leaching losses translated into average and maximum leaching intensities of 0.7 and 75 kg $N{\cdot}Mg^{-1}$ grain, respectively.

This selection of surveyed crops suggests that most Australian farmers manage their N balance well, with only a small minority of crops losing significant N from the system. Combining N losses with their high technical efficiency and low probability for increased productivity from added inputs suggests that many of the Australian farmers surveyed in this study are operating at close to eco-efficient frontiers with regard to N.

Conclusion

The prospect for increasing global agricultural productivity needs to be assessed by comparing current performance of farm enterprises relative to their potential productivity under current and proposed intensification options. Many analyses of “exploitable yield gaps” overstate the likely production gains and their accessibility to farmers. In this methodological context, closing the observed gap between current farmer yields and Y_w values requires distinct actions by farmers in different cropping systems. Some farmers need to improve their technical efficiency to improve their agronomic management and thereby extract the full return from current technologies and their investment in inputs such as N fertilizer. Other farmers have captured these benefits of high technical efficiency and now need to consider increasing their investment in current technologies and thereby move up and along the available production frontier. Still other farmers have both of these intensification options open to them, or neither, being dependent on innovations that create new production frontiers and increased attainable yields.

The production efficiency of grain yields in response to N fertilizer was used as a framework in the diagnosis of the state of agricultural production in contrasting agricultural systems in China (irrigated wheat–maize double-cropping systems), Zimbabwe (rainfed maize systems) and Australia (rainfed wheat systems). More than 3,000 surveyed crop yields in these three countries were compared against yields simulated for currently available varieties and at farmer-specified levels of inputs. Possible pathways for closing the current yield gaps have emerged for each of the three countries. Many of Australia’s commercial wheat farmers achieve high technical efficiency and have little prospect of returns from increasing their N inputs; new technologies and practices are essential to increasing their production without debilitating risks. Many Chinese farmers can reduce N inputs without sacrificing production through more efficient use of their current fertilizer resources; their environment will benefit as well (12). Most African farmers have the opportunity for significant production increases by both improving their technical efficiency and increasing their N inputs, but doing so will require improved management expertise and institutional support in dealing with the higher risks from investing in increased inputs (14, 23).

A key assumption in these analyses is that the studied cropping systems are driven primarily by water and N availability. The production function framework represents Y_w in response to applied N fertilizer; deviations below this frontier are assumed to represent inadequate crop management, which could encompass a whole raft of agronomic issues, including sowing and establishment, supply of other nutrients (especially phosphorous), control of biotic stresses, and efficient harvesting. The main rationale for

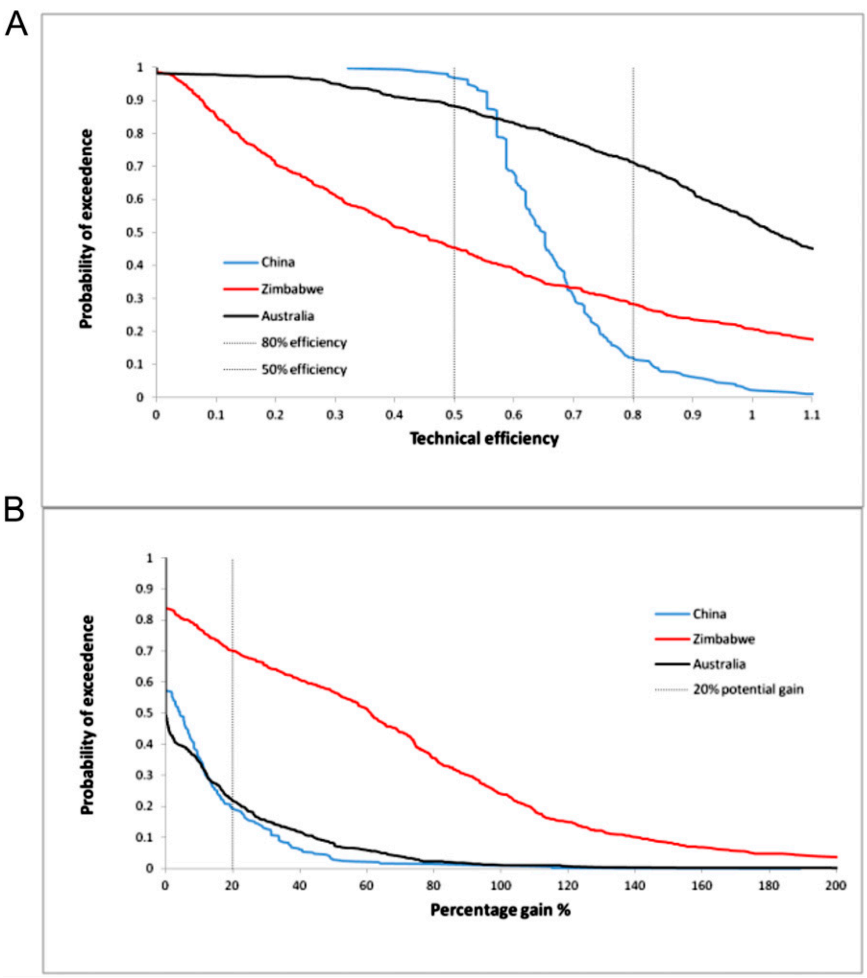

Fig. 4. Probability of exceedence of achieved technical efficiencies (*A*) and percentage production gains from optimal N fertilizer rates relative to actual applied rates (*B*) for Australian wheat crops, Chinese wheat–maize double crops, and Zimbabwean maize crops.

this focus on water and N is because these indeed are the key determinants of cropping system performance worldwide, with the former controlling the performance of rainfed systems and the latter usually representing the highest variable input cost and thus the critical agronomic decision to be made in growing a crop. A second rationale is that N can also represent an environmental concern if lost from the system. Finally, data and models to address crop system responses to water and N are readily available. Other

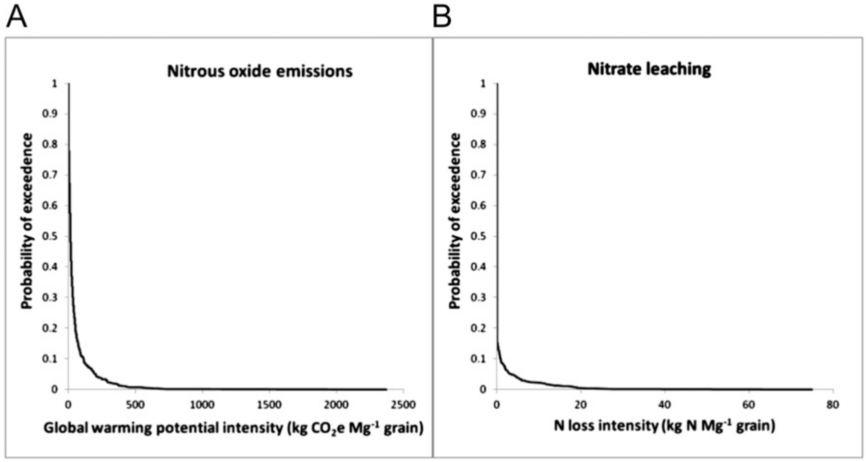

Fig. 5. Probability of exceedence of annual N_2O emissions, expressed as global warming potential intensity (kg $CO_2e{\cdot}Mg^{-1}$ grain) (*A*), and nitrate leaching per unit of grain yield (kg $N{\cdot}Mg^{-1}$ grain) beyond the soil profile (*B*) for Australian wheat crops grown over the period 2004–2011.

candidates for eco-efficiency analysis, such as production responses to other nutrient inputs (eg, phosphorous), measures of soil health (eg, carbon, pH, structure, microbial activity), and trade-offs with native biodiversity loss, could be considered, but the requisite models and on-ground data are largely lacking.

The finding that some Australian farmers are operating close to eco-efficient frontiers, although evaluated here based solely on crop N balance, is encouraging for other farmers in Australia and elsewhere. The challenge now is to find innovations that can continue to enhance the ecological intensification of Australian agriculture. Leading contenders are based largely on genetic improvements, better application of knowledge through climate risk management and precision agriculture, new cost-effective and efficient fertilizer technologies, and the integration of farm enterprises (13). The Australian case study provides an important precedent for African and Chinese farmers faced with their contrasting challenges in improving ecological intensification in their cropping systems.

Cassman (3) asserts that average farm yields must reach 70–80% of the Y_p to meet future food demands. None of the systems surveyed here come close to that value, and the rainfed systems never will (without irrigation); average Y_p values were 61% for the Chinese wheat–maize systems, 14% for maize in Zimbabwe, and 40% for wheat in Australia (Table 1). That said, the irrigated systems in China should be able to reach 80% or more of Y_p, and can do so with the added benefits of reducing N losses to the environment (12). With average wheat yields already at 90% of Y_w, Australian rainfed agriculture will not contribute significantly to future food demands without technological breakthroughs. A hope is for the rainfed systems in Africa, where the yield gaps remain large and potentially exploitable.

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