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DISCUSSION BRIEF

Sustainability Implications of Closing the Yield Gap

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Abstract:

Meeting the growing demand for food will require a major increase in agricultural production, akin to the Green Revolution that dramatically reduced hunger in the last half-century. The approaches that raised yields before, however, cannot significantly raise them beyond current levels, and the environmental impact of agriculture is exceeding a "safe operating space" for humanity. This discussion brief examines ways to sustainably close the gap between potential and actual yields, with a focus on sub-Saharan Africa and South, Southeast and East Asia, where the yield gap is currently greatest. It finds that assessing the yield gap is a challenge in itself, because common measures of productivity fail to account for economic, environmental and other factors that affect yields, especially among smallholders who may be growing multiple crops. There are many examples of agricultural practices that can boost yields while also increasing environmental sustainability and resilience, but the fundamental challenge will be to better understand local conditions and tailor solutions and incentives to specific agro-ecological contexts.

INTRODUCTION

Roughly 7.2 billion people now inhabit the Earth, and by 2050, that number could reach 9.6 billion (UN-DESA 2013a). That would be a 33% increase, but adequately feeding that many people could require increasing food production by twice as much (FAO 2009a) or more (Tilman et al. 2011). In part, this is because food is poorly distributed around the world, with widespread obesity and considerable food waste (Gustavsson et al. 2011) among wealthier populations, but an estimated 870 million people undernourished (UN-DESA 2013b). Also, as incomes rise, people tend to eat more meat (Delgado 2003; FAO 2009b), and animal feed requires a disproportionate amount of crops.

Meeting the growing demand for food is a substantial challenge for agriculture, but not an unprecedented one. In 1950 there were 2.5 billion people in the world (UN-DESA 2013a), and population was rising faster than ever before. Between 1950 and 2000, the population grew by 3.6 million people, or 142% – more in absolute or relative terms than the growth expected between 2000 and 2050 (3.5 million, or 57%). There were probably more underfed people in 1950 as well, although statistics were not collected at the time. The food challenge was met by what has been called the Green Revolution: a remarkable combination of agricultural technologies that raised yields rapidly in much of the world, dramatically increasing food production while limiting the expansion of agricultural land (Evenson and Gollin 2003).

The problem for the future is that the Green Revolution is unlikely be repeated, for two important reasons. First, the techniques used to raise potential yields – that is, the yield achievable on the best land in good conditions – produced a one-time gain. Even including new techniques, such as genetic modification of plants, future yield increases are expected to be smaller and harder to achieve than in the past, at least for grains (Foulkes et al. 2009). Second, the environmental impact of agriculture – along with other human activities – is exceeding a "safe operating space" for humanity (Rockström et al. 2009; Zalasiewicz et al. 2008). Thus, any future yield increases must take global environmental sustainability into account (Foresight 2011; Foley et al. 2011; Balmford et al. 2005).

In the face of declining rates of improvements in potential yield as well as actual yields (e.g. Ray et al. 2012), attention is increasingly focused on closing yield gaps – that is, the difference between potential yields, and the actual yields that farmers achieve on their fields (Lobell et al. 2009; Sadras et al. 2013). Large yield gaps – and therefore the potential to dramatically raise yields – are most apparent in sub-Saharan Africa, which benefited very little from the Green Revolution (Evenson and Gollin 2003; AGRA 2013), but significant yield gaps also remain across the low-income countries and among lower-income farmers in less-poor countries.

There appears to be a particularly large untapped potential to raise yields substantially by improving water partitioning on rainfed lands (Rockström and Falkenmark 2000; Barron 2012; Rockström et al. 2010) Yet decades of experience with agricultural development have shown that the approaches taken to date fall short not only on environmental sustainability, but also in terms of social sustainability, as the benefits are not distributed equitably, and access to land, technology and inputs are all major barriers for the poor (Flora 2010; Martinelli et al. 2010; Jarosz 2012).

The challenge for the future is therefore different from that of the past: to raise yields where the Green Revolution failed to raise them while making agricultural production systems worldwide more sustainable, and to accomplish this in ways that are socially just. This paper focuses on a specific aspect of that challenge: the environmental sustainability implications of closing the yield gap.

ENVIRONMENTAL IMPACTS OF AGRICULTURE

The substantial increase in global food production over the last half-century has been achieved, to a great extent, through the augmented use of inputs such as synthetic fertilizers, pesticides, and herbicides as well as technologies for water appropriation and distribution, plant breeding and disease control. These developments met a fundamental human need, but also exacerbated or created many sustainability concerns – e.g. groundwater depletion, water and air pollution, and loss of biodiversity (Altieri 1998; Wackernagel et al. 2002; Millennium Ecosystem Assessment 2005; Conway and Barbier 2013). Many researchers have pointed to agriculture as a major driver of degradation of the world's natural environment (Wackernagel et al. 2002; Millennium Ecosystem Assessment 2005; IIASTD 2009; Tilman et al. 2011; Holt-Giménez and Altieri 2013). In a study that estimated the burden of the human economy on the natural environment, Wackernagel et al. (2002) concluded that agriculture is one of the most important threats to global biodiversity and ecological function of any single human activity.

Yet improvements in crop yield over the past half-century also addressed an important global dimension of sustainability: the need to preserve land. In most of the developed world, forests and wilderness areas were systematically cleared for centuries to create farmland, but much of that land has since been returned to the wild. In developing countries, meanwhile, food production has increased at many times the rate of agricultural area expansion (Ellis 2011). The benefits of yield increases can be seen in the "planetary boundaries" diagram produced by Rockström et al. (2009) and further developed by Rockström (2010) to show changes over time. In the 1950s, land area was zooming toward the edge of the "safe operating space", while freshwater and nitrogen use remained well within the boundaries. During the 1960s the situation was reversed. The expansion of land area slowed sharply, while nitrogen use shot past the boundaries. Increases in freshwater use were still relatively modest, but that changed in the 1990s, when use began to accelerate. Recently it has become clear that limited phosphorus availability may also constrain future agricultural expansion (Cordell et al. 2009; Schröder et al. 2011). These trajectories of environmental pressure are a common experience in the pursuit of sustainability. Management must solve multiple, partially contradictory objectives within highly constrained systems.

Conventional intensive agriculture is also contributing substantially to global greenhouse gas emissions that drive climate change, to cross-border atmospheric pollution (Hollaway et al. 2012), to changes in the global nitrogen cycle (Vitousek et al. 1997), and to biodiversity loss (Millennium Ecosystem Assessment 2005). At the local level, meanwhile, the documented environmental impacts include accelerated soil erosion and emission of carbon due to land-use change, eutrophication and pollution of surface water bodies, and depletion of underground water reserves.

The social cost of conventional intensive agriculture, meanwhile, has been documented in the area of reduction in the abundance and quality of biodiversity services (Sandhu et al. 2010; Tscharntke et al. 2012), food safety and health (Roberts 2009), the economic and social decline of local farming communities (Altieri 2009; Holt-Giménez 2011), the impoverishment of poor countries through systems of subsidies from richer countries, and the social strife resulting from food price crises (Wodon and Zaman 2010).

These problems should not be seen as an indictment of agriculture: there is no known way to feed the planet in 2050 without disrupting natural systems, and good solutions require a balance between conflicting goals. There are also many ways to arrange global agricultural production in more sustainable ways (Foley et al. 2011). And there are many well-known effective practices, such as conservation agriculture, which minimizes or eliminates tilling to preserve soil organic matter, and thus improve soil quality and water retention capacity. Significant efforts have also been made to reduce fertilizer runoff, irrigation water waste, and other problems.

The view that closing the yield gap requires significant increases in nutrient input – specifically, nitrogen and phosphorus in inorganic fertilizers – is also coming into question. These and other nutrients are fundamental to attaining today's expected yields, and to closing regional and local yield gaps, but closer analyses suggest that adding more fertilizer may bring limited marginal benefits in many farming systems. For example, Sutton et al. (2013) note that in India, the benefit of increased use of nitrogen may be marginal when compared with better management of existing nutrient additions. At a global scale, Sutton et al. (2013) find that better management may also be the answer for several other parts of Asia, whereas in sub-Saharan Africa, especially in areas with large yield-gap challenges, more nitrogen and other essential nutrients will be needed. The challenge will be to ensure sufficient input and management to reduce leakage and inefficient losses in systems, as greenhouse gases (GHGs) or to water bodies.

Limiting environmental pressures is particularly challenging in the context of closing yield gaps in tropical and sub-tropical regions. These areas, where smallholder farming prevails, are also the parts of the world where biodiversity – and biodiversity loss – are highest (UNEP 2007). Agriculture is linked to biodiversity loss: as land is cleared for farming, habitats are disrupted and fragmented; fertilizers and pesticides also affect the ecosystems within which farms are embedded (Altieri 1998; Nellemann et al. 2009).

Moreover, the natural composition of many soils in tropical and sub-tropical regions makes them particularly sensitive, and they can degrade rapidly when the vegetation is cleared and the land is farmed for a few years (Stocking 2003). Still, even in tropical and sub-tropical regions, it is possible to achieve sustainable intensification (Pereira et al. 2012).

CLIMATE CHANGE

As noted earlier, agriculture is a major contributor to global GHG emissions – an estimated 5.9 gigatonnes (Gt) of carbon dioxide equivalent (CO_2e) in 2009, about 13% of total GHG emissions for the year; land use, land-use change and forestry, meanwhile, produced another 2.6 Gt CO_2e, or about 6% of global GHGs (World Resources Institute n.d.). The UN Food and Agriculture Organization reports that since 1990, GHG emissions from agriculture have increased by an average of 1.6% per year (FAO 2013b). Those emissions are primarily non-CO_2 gases such as methane (CH_4) and nitrous oxide (N_2O) – both powerful short-lived climate forcers – from crop and livestock production, including enteric fermentation, manure management systems, synthetic fertilizers, manure applied to soils or left on pastures, decaying or burning crop residues, rice cultivation, and cultivated organic soils (ibid.).

Climate change, in turn, poses enormous challenges for agriculture. Rising temperatures; changes in rainfall patterns; increases in extreme weather events such as torrential rains, floods, droughts and heat waves; and sea-level rise are already affecting agriculture in wealthy and poor countries alike. Climate change is also exacerbating water scarcity, especially in the driest and hottest regions. As the FAO (2013b) notes, the poorest farmers are the most vulnerable to these impacts, because land and water will become scarcer, and limited technical and financial resources will make it hard for them to adapt.

A number of agricultural practices and strategies are available to make agriculture more resilient to climate change impacts and to reduce GHGs and even capture carbon. The FAO describes the collection of these measures – along with approaches to providing the technical, policy and investment conditions to support them – as "climate-smart agriculture" (FAO 2013a). The purpose of CSA is to operationalize sustainable agricultural development explicitly within the parameters of climate change.

There are numerous opportunities for reducing GHG emissions in agriculture (Smith et al. 2008). One area of particular interest in the context of closing the yield gap is soil carbon sequestration; the world's agricultural and degraded soils now capture considerably less carbon than was previously stored in soils, and practices that increase soils' carbon content – such as no-till farming, cover crops, manure and sludge application, and many others – can also increase yields (Lal 2004). Other ways to reduce GHG emissions which are also broadly compatible with sustainability goals include limiting nitrogen fertilizer use only to what crops can use efficiently (Cassman et al. 2003; Galloway et al. 2003); improved water (Follett et al. 2001; Lal 2004) and rice management (Yagi et al. 1997; Wassmann et al. 2000) and agro-forestry (Guo and Gifford 2002). Improved livestock and manure management (Smith et al. 2008) can also significantly reduce emissions. Many of these strategies have both adaptation and mitigation value; Smith and Olesen (2010) find a great deal of potential for synergies between both goals in the context of agriculture.

The impact and viability of climate-smart agriculture options differs by region and depends on the climate, social setting, historical patterns of land use, and other conditions (Smith et al. 2008). Even in industrialized countries, adoption of these practices may be hindered by many factors, ranging from farmers' own perceptions, to the political economy of agriculture (see, e.g., Stuart et al. 2014). In developing nations, lack of capital, insecure land tenure and inadequate technology are particularly significant barriers (FAO 2013a). In addition, there is a great need to provide knowledge and build technical skills among farmers, especially smallholders in low-income countries (Branca 2012).

YIELD AND YIELD GAPS

Within agronomy, and in national and international statistics, agricultural yield is defined as the amount of valuable (or "economic") plant matter per unit area. So, for example, the yield of maize is expressed in tonnes of grain per hectare. This "standard yield" can be written

$$Y_S = \frac{P_E}{A},$$

where Y_S is standard yield, A is the land area on which the crop is grown, and P_E is production of the economic part of the plant. Standard yield is a good indicator of agricultural productivity for many purposes, but not for all, and particularly when environmental sustainability is the goal. Measuring grain (or root, tuber, seed, and other readily edible plant parts) will understate the value of crops if the residue is used as feed, fuel, fertilizer, or building material. It can also understate the value of mixed cropping systems, whether combinations of different crops or crop-livestock systems, and multiple-cropping systems, in which more than one crop is grown on a single field in a year. The yield per hectare of any one component of the mixed system may be relatively low, but the combination can deliver substantial calories or income and be less vulnerable than a single crop to environmental stresses and pests. This section summarizes the current definition of yield gap and then presents alternatives that try to capture some of these other dimensions.

Yield gap

Yields that farmers actually achieve on their fields are affected by the plants they choose to grow (the genetic material, G), prevailing environmental conditions E (rainfall, temperature, sunlight, pests, and other factors), the soils S on which they grow their crops, and their management strategies M (weeding, crop spacing, inter-cropping, fertilizer, irrigation, and other factors). Yield gaps compare these *realized* yields to a theoretical alternative. The alternatives are defined by setting G, E, or M to an optimum:

- **Water-limited yield** Y_{SW} relaxes M by asking for the best possible yield under water-limiting conditions for a particular type of existing crop;
- **Potential yield** Y_{SP} relaxes both M and E by asking for the best possible yield for a crop in a climate to which it is suited, and can also relax M, E, and S together, for the potential yield on the most suitable type of land;
- **Theoretical yield** Y_{ST} relaxes all factors: G, E, S, and M by asking for the maximum possible yield from a particular plant species.

Counterfactuals are always difficult to establish, and estimating water-limited and potential yields is challenging. Research is ongoing on the best techniques to use, whether to compare to best realized yield or to models, and when to use detailed physiological models and when more rough-and-ready models might be suitable (Lobell et al. 2009; Sadras et al. 2013).

Yield gaps normally refer to the difference between realized yields and either potential yield (for irrigated conditions) or water-limited yield (for rainfed conditions). A problem with the yield gap concept is that farmers are rarely aiming to maximize grain yield. Instead, they try to maximize a contribution to their income and livelihoods in relation to labour and other inputs. On a farm with unlimited access to irrigation in an area with predictable weather, the goal might be maximum profit. Farmers growing food both for themselves and the market may try to meet their households' needs before focusing on the cash crops. Some of these factors may be points of intervention to shrink yield gaps, but some are irreducible. As a rule, the top realized yields on commercial farms are about 20% below the theoretical potential (Lobell et al. 2009). Thus Sadras et al. (2013) define the yield gap, ΔY_S, as the difference between the realized yield and 80% of the potential or rain-limited yield:

$$\Delta Y_S = \left(0.8Y_{SP} - Y_S\right) \text{ or } \left(0.8Y_{SW} - Y_S\right).$$

Productivity gain ratios R_{SP} and R_{SW} can then be calculated as ratios of yields. This will turn out to be an easier calculation to generalize to alternative definitions of yields:

$$R_{SP} = \frac{1}{0.8}\frac{Y_S}{Y_{SP}},\ R_{SW} = \frac{1}{0.8}\frac{Y_S}{Y_{SW}}.$$

An important caveat here is that many factors beyond farmers' control can also affect yields. For example, research on ozone (O_3) shows that this pollutant has been linked to yield losses of up to 50% for wheat, rice and legumes (Emberson et al. 2009). More research on the implications of air pollution for yield gaps are particularly important in areas with heavy urbanization and industrialization, such as South, Southeast and East Asia, which have been shown to have both elevated O_3 and potential yield impacts (Van Dingenen et al. 2009). Small-particle pollution could also affect both potential and actual yield level (Chameides et al. 1999). It is crucial to better understand and quantify the impact of air pollution on yields, as overcoming them may require actions that go beyond the agriculture sector.

Land equivalent ratio

When crops are intercropped – that is, grown together on the same area of land – their yields are different than when they are grown by themselves. Suppose there is a collection of N crops, labelled $i = 1,...,N$. When grown individually each has a standard yield Y_i. When they are intercropped on an area A, each crop will produce less than if it were grown by itself on the same area. Suppose that each crop has an economic production of P_i when grown together, and define the yield in the intercropped system

$$y_i = \frac{P_i}{A}.$$

We generally expect y_i to be less than Y_i. The land-equivalent ratio (LER) (Mead and Willey 1980) is calculated by comparing the land area used to grow the crops together to the land area A_M that would be required to grow each crop as a sole crop (or mono-crop) on its own individual plot of land to get the same levels of production P_i. Because production levels can be calculated from the communal yields y_i, this area can be calculated as

$$A_M = \frac{Ay_1}{Y_1} + \frac{Ay_2}{Y_2} + \cdots \frac{Ay_N}{Y_N} = A\left(\frac{y_1}{Y_1} + \frac{y_2}{Y_2} + \cdots \frac{y_N}{Y_N}\right).$$

LER is then calculated by dividing A_M by A:

$$\text{LER} = \frac{y_1}{Y_1} + \frac{y_2}{Y_2} + \cdots \frac{y_N}{Y_N}.$$

The land-equivalent ratio is a measure of land savings that can be gained when growing crops together rather than separately, and is an improvement when it is greater than one.

As with the yield gap, computing the LER requires a counterfactual, the yields of each crop when grown separately. Even when these have been measured prior to switching to inter-cropped plants, changes in the weather, soil biota, pests, and other factors can complicate any comparisons (Fukai 1993; Willey 1985; Mead and Willey 1980). For example, Echarte et al. (2011) found that in the first year, a soybean-sunflower intercrop had an LER greater than one, but it dropped to very close to one in the second year, meaning no change in productivity, apparently because of differences in seasonal weather.

The LER is not an ideal measure, although it has the great value of simplicity, an important criterion for practical applications (Wojtkowski 2008). One key criticism is that it does not take time into account: Hiebsch and McCollum (1987) found that when they re-calculated LER values from published studies using an alternative measure that includes time, the benefits of intercropping disappeared. Time is also important for sole crops grown in sequence on the same land (Evans 1996). However, Fukai (1993) argues that Hiebsch and McCollum's measure may also not be the best way to assess potential benefits of intercropping, and proposes alternative measures. Two observations from this debate are important for the present report: even when time is included in the measure, intercropped systems perform about as well as sole production systems, and there is no agreement on the best way to measure the productivity of intercropped systems. Indeed, Weigelt and Jolliffe (2003) found at least 18 different indices measuring the effects of plant competition, including LER.

Taking farmers' goals into account

The land-equivalent ratio has another disadvantage that was pointed out by its creators (Mead and Willey 1980). It pays no attention to what the farmer wants out of his or her land, and the most biologically productive intercropping system may not be the one that delivers the mix of crops that the farmer wants within the constraints that the farmer faces (Willey 1985). One option is to use economic measures, such as a revenue-equivalent or cost-equivalent ratio. Distinguishing costs from revenue is important, as farmers with abundant land but limited access to external farm inputs may prefer to focus on cost-saving measures rather than revenue-increasing measures (Wojtkowski 2008).

In general, the yield gap approach ignores farmers' goals and constraints, in part for good reason. If yields could be much higher than they are, then not only could more food be produced, but farmers may be able to get more revenue and support higher costs. However, it can obscure the reasons for yield gaps. For example, in mixed crop-livestock systems, crops are grown partly for grain and partly to generate residues, which are then used as feed. The livestock often graze on the stubble in fallow fields while producing manure that fertilizes the crops. Using the standard measure of yield, residue production is ignored, so its contribution to the farming system is discounted.

Agro-ecosystem productivity

Ultimately, a particular climate-ecological region has an inherent long term sustainable production capacity of biomass represented by the net primary production (NPP) attained in a natural ecosystem on the same land. Natural ecosystems develop over long times, and under human disturbance, ecosystems free of human activity are rare. More often are found highly managed agro-ecological systems providing humanity with food, fibres and fodder, and other products. Various assessments of NPP show that anthropogenic impacts can positively or negatively alter natural levels (Haberl et al. 2007; de Jong et al. 2011), along with changes in, for example, water flows (Keys et al. 2012; Gordon et al. 2005).

Gliessman (2000) suggested an agro-ecosystem productivity index PI given by the ratio of the stock of biomass to annual NPP,

$$\mathrm{PI} = \frac{\text{accumulated biomass}}{\mathrm{NPP}}.$$

This index is not comparable to the indices introduced above, because it has units of time, rather than being dimensionless. More fundamentally, it is not improved by increasing output. Instead, the PI index can be increased by building up stored biomass in the system. The thinking behind this is that the accumulated biomass is supporting a complex ecosystem that helps capture and provide nutrients; buffer the activity of pests and diseases; and improve soils (Gliessman 1995).

High-input vs. organic agriculture

The discussion of Gliessman's PI index raised the important point that using the yield gap as a guide presumes that maximum production per unit of land is the top goal. Generally, although not always, yields under organic systems are lower than in high-input systems (Seufert et al. 2012; de Ponti et al. 2012). Thus switching from high-input to organic agriculture would, all else remaining the same, require an increase in agricultural land area to produce the same amount of food. However, it could also have environmental benefits. In today's world, in which agriculture has already taken us outside a "safe operating space", it is not obvious what the right balance of yield and inputs might be.

Keeping Wojtkowksi's (2008) admonition in mind that indicators should be simple, one possibility for comparative indices is to reduce potential and water-limited yields by a factor to capture the benefits of low-input agriculture. Gaps between organic and high-input agriculture are lower on rainfed fields than on irrigated fields, but on average, organic yields are 75% of yields under high-input systems (Seufert et al. 2012). For low-input systems, actual yields could be compared to 75% of 0.8, or 0.6, of yield potential. This gives the following ratios, suitable for low-input intercropped systems,

$$R_{LIP} = \frac{1}{0.6}\left(\frac{y_1}{Y_{SP1}} + \frac{y_2}{Y_{SP2}} + \cdots \frac{y_N}{Y_{SPN}}\right),\quad R_{LIW} = \frac{1}{0.6}\left(\frac{y_1}{Y_{SW1}} + \frac{y_2}{Y_{SW2}} + \cdots \frac{y_N}{Y_{SWN}}\right).$$

For sole crops the ratios become

$$R_{LSP} = \frac{1}{0.6} \frac{Y_S}{Y_{SP}}, \; R_{LSW} = \frac{1}{0.6} \frac{Y_S}{Y_{SW}}.$$

While Gliessman's (2000) PI indicator is meant to support a different goal – maximizing biomass stocks – it also suggests a comparison to a yield somewhat below potential, because part of the yield should go toward maintaining standing biomass stocks rather than the harvest.

Even without switching to organic agriculture, it is possible to reduce fertilizer application (Tilman et al. 2011) and other external inputs without substantial changes in yields. A more balanced indicator might somewhat penalize external inputs, so that gains in yields would be partly offset by increases in external inputs, but this would lead to "apples-to-oranges" comparisons. It is also important to note that in some regions, yields cannot be increased without adding nutrients – from chemicals, organic matter, or both.

Causes of yield gaps

Yields can be below potential because of insufficient or imbalanced nutrients; insufficient or excess water; pests, diseases, and weeds; soil problems; physical damage; poor seed; and suboptimal planting. They can also be low because it is not profitable for farmers to raise them further, because of resource constraints, or because of lack of knowledge (Lobell et al. 2009). Attributing yield gaps to specific causes is challenging – it is easy to misattribute causes, and causes are often interconnected: diseases can be exacerbated by poor nutrition; suboptimal planting can be caused by poor information; and insufficient nutrients may be explained by economic constraints.

Ultimately, closing yield gaps is fundamentally about farmers practicing the best known management solutions for their crops and locations. Many practices that increase yields also provide environmental benefits – not only in terms of GHG reduction, but also air and water quality, biodiversity and more. The value of these practices, however, may be underestimated if measures of agricultural productivity don't go beyond crop per unit of land, or crop per drop of irrigation. This is especially true in complex agro-ecosystems with mixes of crops, livestock and horticulture, where farmers are poor and have little technology.

Second, global analysis does not necessarily mean local appropriate solutions. Knowing that inadequate nutrients or water supplies limit yields can provide valuable insights, but closing yield gaps at the local level requires a diverse portfolio of strategies, technologies and incentives, which can then be applied in different combinations to suit different farmers' needs. That is the key insight behind the recently launched TAGMI tool (Targeting AGwater Management Interventions – http://www.seimapping.org/tagmi/), which allows planners in the Volta and Limpopo basins to identify the agricultural water management technologies that are likeliest to succeed in individual districts.

CONCLUSION

Compelling evidence points to a need to find sustainable ways to increase agricultural productivity, especially in regions where substantial yield gaps now exist. While sustainable intensification promises to offer the best potential for reaping both agro-ecological and socio-economic benefits, several challenges need to be addressed to enable sustainable intensification to take hold and flourish. These include:

- Identify appropriate land management systems (specific to major agro-ecological zones) that can narrow the yield gap while simultaneously sustaining flows of ecosystem services.

- Develop alternative measures of agricultural production that better capture the productivity of intercropped, multiply cropped, mixed-crop and livestock systems, and agro-ecosystems.

- Match strategies to farmers' current goals and constraints. In the long run, provide an enabling framework for cross-sectoral collaboration in up-scaling and mainstreaming the adoption and use of sustainable agriculture practices (especially among small and medium-scale farmers who form the bulk of agricultural producers in sub-Saharan Africa and South, Southeast and East Asia).

- In working to close yield gaps, include measures to avoid or reduce GHG emissions.

- Enhance the flow of intellectual, governance and investment resources between relevant national and international stakeholders in the agricultural and natural resources sectors. The objective should be to attain higher levels of sustainability by fostering the development of policy, institutional, and regulatory reform processes in the relevant sectors.

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