Agriculture in 2050: Recalibrating Targets for Sustainable Intensification

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The prevailing discourse on the future of agriculture is dominated by an imbalanced narrative that calls for food production to increase dramatically—potentially doubling by 2050—without specifying commensurate environmental goals. We aim to rebalance this narrative by laying out quantitative and compelling midcentury targets for both production and the environment. Our analysis shows that an increase of approximately 25%–70% above current production levels may be sufficient to meet 2050 crop demand. At the same time, nutrient losses and greenhouse gas emissions from agriculture must drop dramatically to restore and maintain ecosystem functioning. Specifying quantitative targets will clarify the scope of the challenges that agriculture must face in the coming decades, focus research and policy on achieving specific outcomes, and ensure that sustainable intensification efforts lead to measurable environmental improvements. We propose new directions for research and policy to help meet both sustainability and production goals.

Keywords: food demand, crop yield, food security, environment, policy

The prevailing discourse on the future of agriculture is rife with the assertion that food production must increase dramatically—potentially doubling by 2050—to meet surging demand. Many authors also call for agriculture to become more environmentally sustainable, but with little urgency and few quantitative targets. The result is an imbalanced narrative that heavily privileges production over conservation. This imbalance persists despite calls in the growing sustainable intensification (SI) literature to treat food production and environmental protection as equal parts of agriculture's grand challenge (Robertson and Swinton 2005, Garnett et al. 2013, Pretty and Bharucha 2014, Rockström et al. 2017).

We aim to rebalance this narrative by laying out quantitative and compelling SI targets for both production and the environment. These goals will clarify the scope of the challenges that agriculture must face in the coming decades, focus research and policy on achieving specific outcomes, and ensure that SI efforts lead to measurable environmental improvements.

Our targets are based on the following standards: (a) SI production goals should aim to meet projected global food demand while recognizing that factors beyond aggregate production also affect hunger and malnutrition (FAO et al. 2015, Schipanski et al. 2016), and (b) SI environmental goals should aim to restore and maintain ecosystem functioning in both managed and natural systems (Neufeldt et al. 2013, Rockström et al. 2017).

Many authors call for production increases of 60%–100% by 2050, based on two recent food-demand projections (Tilman et al. 2011, Alexandratos and Bruinsma 2012). These goals appear clear and compelling, but they exaggerate the scale of the production increase needed by 2050 because they misinterpret the underlying projections and ignore recent production gains. Moreover, the projections are often simplified into a goal of doubling yields, which serves as an urgent rallying cry for research, policy, and industry (Monsanto 2008, Foley et al. 2011, Tilman et al. 2011, Ray et al. 2013, Long et al. 2015, Buckley 2016). This, in turn, fosters a produce-at-all-costs mentality, which may exacerbate existing environmental challenges by increasing the use of fertilizers, pesticides, irrigation, and tillage.

In contrast, current SI environmental targets are unclear and unlikely to inspire action. Most authors agree that uncultivated land should not be converted for crop production (e.g., Garnett et al. 2013, Pretty and Bharucha 2014). Beyond this, however, stated goals diverge. They range from the basic—not "increasing agriculture's environmental footprint" (Buckley 2016)—to the more aggressive—"major reductions in environmental impact" (Garnett et al. 2013). Some sustainability goals would even result in increased environmental degradation, such as when marginal reductions in per-unit impacts are coupled with doubled output (Monsanto 2008).

Our analysis shows that, largely because of recent production gains, an increase of approximately 25%–70% above

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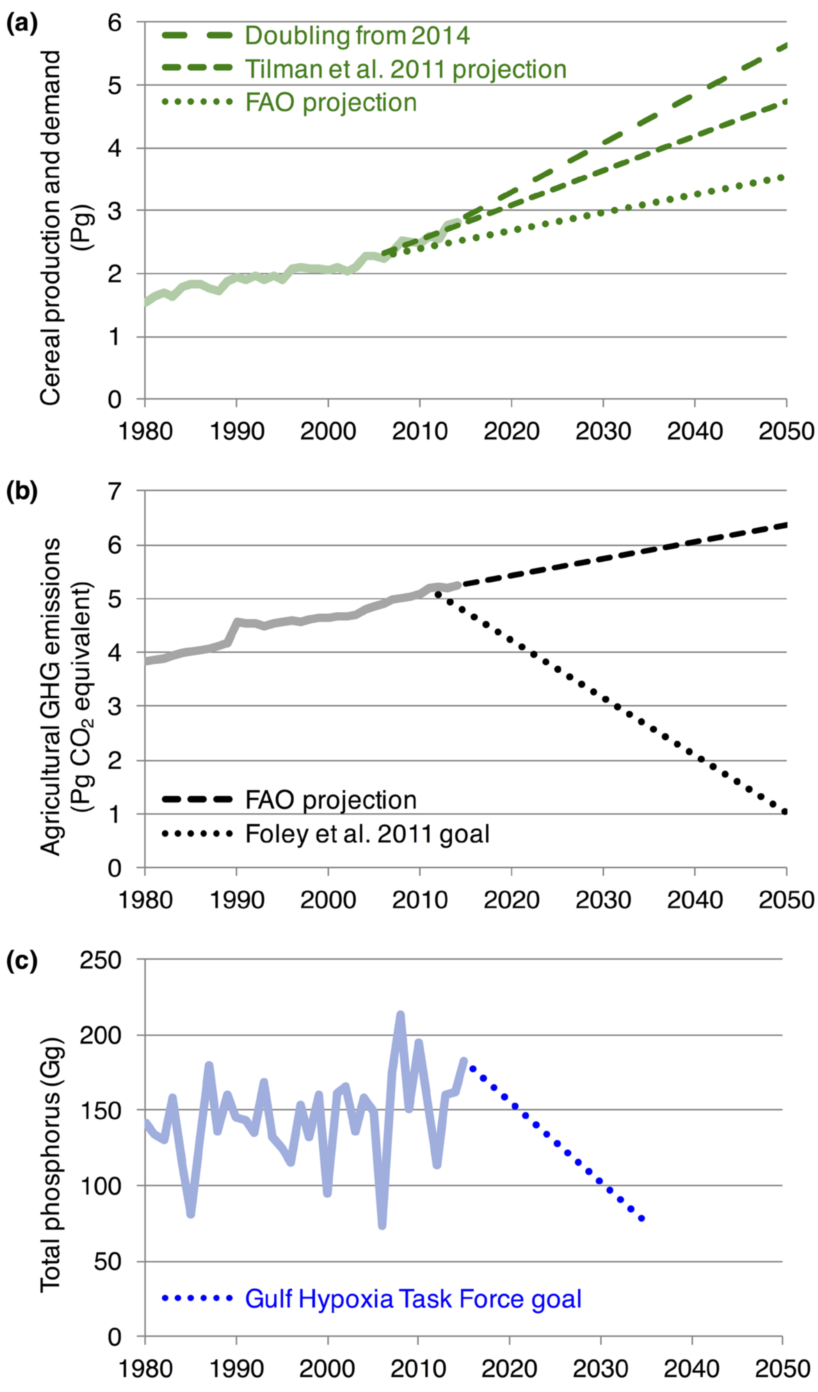

Figure 1. Food demand is projected to climb, while environmental impacts must plummet. Calls to double crop production from a recent baseline imply growth rates outside of the range of empirical projections. Meanwhile, agriculture's environmental impacts need to fall rapidly to protect critical ecosystem functions. (a) Historical and projected global cereal production and demand (in petagrams). (b) Historical and projected direct greenhouse gas (GHG) emissions from agriculture and 2050 goal. (c) Historical total phosphorus loading in the Mississippi–Atchafalaya River Basin and 2035 goal (in gigagrams). Historical data are shown in solid lines, and future projections and goal trajectories are shown in dashed or dotted lines (see supplemental tables S1 and S3). Pg, petagram; Gg, gigagram. Sources: MRGMWNTF 2015, Foley et al. 2011, Tilman et al. 2011, Alexandratos and Bruinsma 2012, USGS 2015, FAO 2016.

current production levels may be sufficient to meet 2050 demand (figure 1a, supplemental table S1). Calls to double food production from today's levels are not supported by existing projections. Although even a 25%–70% increase will be challenging, global agricultural output is at least on the right trajectory. In contrast, agriculture's environmental performance is going in the wrong direction: Aggregate impacts are increasing and must drop sharply over the coming decades (figure 1b–c, supplemental table S3).

We review and update the main projections of world food demand, discuss examples of environmental improvements needed by 2050, and propose new directions for research and policy to help meet both sustainability and production goals. Our objectives are to clarify the overarching productivity and environmental goals of SI and to recalibrate the narrative on the future of agriculture. Therefore, we do not address the related social, economic, and geopolitical dimensions of SI (Loos et al. 2014, Pretty and Bharucha 2014, IPES-Food 2016); heterogeneity among regions (Alexandratos and Bruinsma 2012, Mueller et al. 2012, Cunningham et al. 2013, van Ittersum et al. 2013); or the merits of different management philosophies (Cassman 1999, IAASTD 2009, Bommarco et al. 2013, Tittonell 2014). Rectifying the prevailing SI narrative is crucial because it is already shaping the future of agricultural research and policy (e.g., USDA 2015, Buckley 2016), with potentially dramatic consequences for the future of food production and the environment.

Food-demand projections

Food demand in 2050 is projected to rise as the global population crests 9.7 billion people (UN 2015) and greater wealth drives up per-capita consumption, especially of resource-intensive animal products (Alexandratos and Bruinsma 2012). Public and scientific discourse on the subject focuses primarily on two studies (Tilman et al. 2011, Alexandratos and Bruinsma 2012). First, Alexandratos and Bruinsma (2012) of the United Nations (UN) Food and Agriculture

Organization (FAO) projected a 60% increase in demand from a 2005/2007 baseline using a price-weighted index of food commodities. Second, Tilman and colleagues (2011) projected that demand for calories and protein from human-edible crops will increase by 100% and 110%, respectively, from a 2005 baseline. Both of these projections account for crops used as animal feed and, to a limited extent, as biofuel feedstock.

These projections are complex and are commonly misinterpreted. First, the FAO projection of a 60% increase is frequently misquoted as a 70% increase when authors cite an earlier FAO report (Alexandratos 2006). Second, the price-weighted basis of the FAO figures implies a larger increase in crop demand than is actually projected on a mass basis: For example, FAO projects only a 46% increase in cereals demand (Alexandratos and Bruinsma 2012). Most importantly, authors often ignore the base year of the projections (Foley et al. 2011, Ray et al. 2013, Long et al. 2015, Daryanto et al. 2016), implying that the projected increase must occur from today's production levels. For both of these projections, the base year is now a decade past, and production has increased substantially in this time (table S1). This error is particularly misleading when authors explicitly graph 2050 demand as a doubling from current levels (e.g., Long et al. 2015).

We use global demand for cereals as a proxy for total crop demand to illustrate the production increase needed by 2050. Cereals are the world's dominant crops. In 2013, they were grown on 47% of global cropland and provided 63% and 56% of calories and protein, respectively, from human-edible crops (table S3; FAO 2016). Of course, ending hunger and malnutrition will require multiple crop types, including pulses, roots, vegetables, and fruits, many of which will need to be produced and marketed locally. Our focus on aggregate global cereal demand does not imply that meeting this demand would ensure global food security. Instead, our updated projections are intended to illustrate agriculture's big-picture production challenge.

We build and update approximations of the FAO (Alexandratos and Bruinsma 2012) and Tilman and colleagues' (2011) projections. The FAO projected cereals demand in 2050 directly (Alexandratos and Bruinsma 2012). Tilman and colleagues (2011) did not, so we approximate their projection with a simple doubling of demand from a 2005 baseline. We also linearly transform both estimates to account for differences between the original projections' assumed 2050 population and the latest United Nations analysis (UN 2015). We use the most recent FAOSTAT data (FAO 2016), from 2014, as the baseline for our projections. All data and projections are available in the supplemental materials.

Our updates to the FAO (Alexandratos and Bruinsma 2012) and Tilman and colleagues' (2011) projections indicate that production of cereals must only increase 26% and 68% from 2014 levels, respectively, to meet 2050 demand (figure 1a, table S1). Rapid production growth in recent years

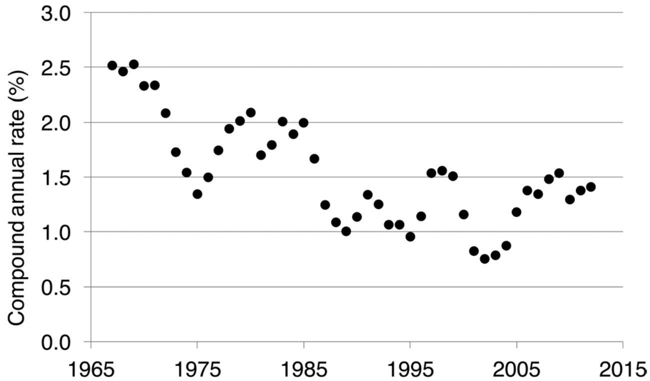

Figure 2. Decrease in world cereal yield growth rate over time. To double by 2050 from a 2005 baseline, yield growth would have to be maintained at 1.5% per year. Doubling from a 2014 baseline would require yield growth of 1.9% per year. Each point represents the compound annual growth rate of global average cereal yields over the 5 previous years (FAO 2016). To smooth interannual variation, growth rates were calculated using 5-year moving average cereal yields.

has made substantial progress toward the original projected increases of 46% and 100%. Cereal production increased 24% from 2005 to 2014 because of both yield improvements and the expansion of cropped area (supplemental tables S1 and S5; FAO 2016). The production of oilcrops—which account for most of the remaining calories and protein from human-edible crops—increased even more, by 39% (supplemental tables S2 and S4; FAO 2016). Projected 2050 demand for oilcrops is 46% higher than 2014 production levels based on the FAO projection and 50% higher based on a doubling from 2005 (table S2).

The discrepancy between the two cereal demand projections—26% versus 68%—is largely due to differences in model assumptions. The FAO (Alexandratos and Bruinsma 2012) assumed a lower rate of annual GDP growth than Tilman and colleagues (2011): 2.1% as compared with 2.5%. The FAO also adjusted its projection to account for potential saturation of meat consumption in the largest developing country, China, and cultural factors limiting the growth of meat consumption in the second largest, India (Alexandratos and Bruinsma 2012).

The two projections have drastically different implications for the future of crop production. Under the FAO projection, the rate of average annual cereal yield growth could fall gradually over the next 35 years and still meet demand using only existing cropland. To double from a 2005 baseline, in contrast, cereal yields would have to grow continually at a compound annual rate of over 1.5%, which has not been achieved consistently since the mid-1980s (figure 2). Doubling yields by 2050 from a recent baseline—the increase implied when authors do not specify the base year for doubling—would require an even higher annual yield growth rate of 1.9% per year.

Sustaining these rates of average annual yield growth until 2050, if it is even possible, would require widespread intensification of fertilizer, pesticide, and irrigation regimes. This level of intensification would almost certainly increase agriculture's impact on water quality, aquifers, wildlife, and the climate (Robertson and Swinton 2005, Foley et al. 2011, West et al. 2014). SI production goals should therefore be stated carefully to avoid furthering a production-at-all-costs approach to agriculture. Goals should reflect the updated projection that production must increase approximately 25%–70% from recent levels to meet demand in 2050. Calls for doubling current production by 2050 should be avoided.

Environmental goals

In contrast to the literature on food demand, there has been little discussion of specific environmental goals for agriculture in 2050 or of the sector's trajectory toward such goals. Instead, the prevailing discourse often focuses on increasing efficiency or improving general "sustainability," which gives the impression that marginal environmental improvements are sufficient (Petersen and Snapp 2015). To illustrate the true scope of agriculture's environmental challenges, we analyze the sector's performance against quantitative targets that have been proposed to achieve specific environmental outcomes: mitigating climate change and limiting eutrophication in the Gulf of Mexico.

Agricultural production activities directly contribute 11%–13% of the world's total anthropogenic greenhouse gas (GHG) emissions (IPCC 2014). Indirect emissions from land-use change in agriculture and forestry contribute another 12% (IPCC 2014). To avoid the worst impacts of climate change, Foley and colleagues (2011) called for an 80% reduction in agricultural GHG emissions. Since direct agricultural GHG emissions have been steadily climbing, achieving this level of reduction by 2050 would require an abrupt shift in emissions trajectory (figure 1b, table S3).

Losses of agricultural nutrients to waterways contribute to hypoxic "dead zones" downstream, threatening marine life and fisheries in coastal regions throughout the world. The hypoxic zone in the northern Gulf of Mexico is fed by the Mississippi–Atchafalaya River Basin system in the central United States, where riverine nitrogen (N) and phosphorus (P) are primarily from agricultural sources. The second largest in the world, this dead zone reached 22,000 square kilometers (km^2) in 2002 and averages 13,650 km^2 per year (EPA 2016). In 2001, an intergovernmental task force set a goal to reduce the average size of the dead zone to 5000 km^2 by 2015, which would require reducing annual N and P loading to a level 45% below the 1980–1996 average (MRGMWNTF 2001, 2008). This goal was not met, and the task force recently extended the deadline to 2035 (MRGMWNTF 2015). As figure 1c shows, P loading has been increasing, and meeting the 45% reduction goal would require a significant shift in trajectory (see also table S3). We illustrate this goal using P data because the trends for total N and reactive N are diverging and the Gulf Hypoxia Task Force goal applies only to total N. Because total N has been declining more rapidly than reactive N, using total N would indicate greater progress toward the goal than has actually been made.

These two examples show that agriculture still faces large environmental challenges, but they are not meant to imply that the sector has not made any progress. Indeed, US agriculture has improved in important areas, including by cutting sheet, rill, and wind erosion by 43% between 1982 and 2007 (USDA 2011) and by beginning to reduce N losses in the Midwest (McIsaac et al. 2016). However, both US and global data on concerns ranging from biodiversity loss and land conversion to irrigation-water withdrawals—in addition to GHG emissions and nutrient pollution—indicate that agriculture leaves a large and growing footprint (Foley et al. 2011, West et al. 2014, Haacker et al. 2015). Clearly, environmental sustainability cannot play second fiddle to intensification; efforts to increase food production and reduce aggregate environmental impacts must go hand in hand.

Agriculture's path to 2050

Meeting food demand while maintaining functioning ecosystems will require a recalibrated SI strategy, in which up-to-date production goals are coupled with quantitative environmental targets. Research and policy should pivot to align with this strategy, both in the United States and globally. Here, we focus on the US context.

The research enterprise led by the National Science Foundation and the US Department of Agriculture (USDA) should prioritize efforts to identify and meet quantitative production and environmental goals. First, research is needed to specify targets in both categories. There is a particularly urgent need to quantify the reductions in pollution and land degradation that must be achieved to sustain functioning ecosystems at multiple scales (Neufeldt et al. 2013, Rockström et al. 2017). These goals will need to be refined periodically as new information becomes available, given the uncertainty of long-term projections.

Second, applied agricultural research should focus on developing production systems that can simultaneously meet both production and environmental targets while helping farmers adapt to a range of emerging challenges, such as mounting water shortages (Falkenmark 2013, Elliott et al. 2014), pesticide resistance (Mortensen et al. 2012), yield plateaus (Grassini et al. 2013, Ray et al. 2013), and the changing climate (Challinor et al. 2014). The technical challenge of such a fundamental transformation in production systems is daunting, and meeting both sets of goals will require navigating complex trade-offs (Robertson and Swinton 2005, Neufeldt et al. 2013, Davis et al. 2016). However, establishing clear targets will help researchers focus on these long-term challenges.

Achieving both production and environmental goals will require shifts in US agricultural policy. Current policy heavily favors production, including through crop insurance and revenue- and price-based subsidy payments for commodity crops. These programs carry only minimal environmental requirements, which provide limited protection against erosion and the loss of some wetlands and grasslands, but fail to target nutrient loss, air quality, GHG emissions, and other concerns. Conservation incentive programs help producers implement many environmentally beneficial practices, but they are not structured to produce maximum benefits. Moreover, many environmental regulations currently exempt agricultural activities. To bring US policy in line with future needs, producers who receive subsidies should be required to meet more stringent environmental standards, conservation programs should be reformed to tie payments to quantified outcomes (Winsten and Hunter 2011), and effective regulatory backstops should be instituted to control the most environmentally damaging practices. Quantitative targets can help guide these policy efforts and promote effective collaborations among researchers, farmers, government agencies, and civil-society groups. The Danish government's pesticide strategy, which aims to reduce pesticide loads by 40%, is one promising example of using quantitative targets to collaboratively set agroenvironmental policy (DME 2013).

The goals of sustainable intensification extend beyond aggregate production and environmental performance. Additional policy efforts are needed to manage food demand by reducing food waste (West et al. 2014) and shifting diets (Davis et al. 2016). We must also halt cropland expansion (Cunningham et al. 2013) and ensure that the world's poorest people have secure access to nutritious food (FAO et al. 2015). Total land in agriculture has risen since 2005 in Africa, South America, and Asia (supplemental table S6; FAO 2016), indicating continued land conversion at the expense of native ecosystems, and conversion continues in the United States as well (Lark et al. 2015). Approximately 795 million people are hungry today, despite adequate global food production, because poverty, lack of infrastructure, poor governance, natural disasters, and political unrest restrict food access (FAO et al. 2015). These problems must be addressed even as production increases and pollution plummets.

Conclusions

We call on researchers, policymakers, and farmers to embrace this recalibrated vision of sustainable intensification. Time is short: The annual cycle of planting and harvest gives farmers fewer than 35 chances to transform their production systems by midcentury. Scientists also face a limited number of opportunities to develop and test new production and conservation strategies. As a group of young agricultural scientists (and one senior scientist), this is the challenge of our careers. By the time our generation retires, agriculture's 2050 goals must be met.

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Supplemental material

Supplementary data are available at *BIOSCI* online.

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