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Loomis Review

# Issues for cropping and agricultural science in the next 20 years

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ABSTRACT

This position paper honours agricultural scientist and colleague, Professor Bob Loomis, by discussing the urgent global challenge of food security and the related impacts on the environment facing agricultural science and society in the next critical 20 years. It uses the concepts of potential and actual (farm) crop yields and the yield gap between them to assess current and future opportunities for food supply to satisfy increasing demand. The cropping world is seen in two parts. The first part predominantly comprises low-input farming with very large yield gaps and a faster growing demand that can only be met with increasing imports. For these regions, a well-established strategy is outlined for crop intensification through yield-gap closure that is essential for reducing rural malnutrition and poverty, and curtailing the likelihood of high food prices. For success, it must be complemented with strategies to remove the serious institutional and infrastructural barriers faced by farmers. The second part has more or less intensified, and yield gaps are generally small to moderate: it will fairly comfortably meet the demand from population growth. For these regions, some further yield gap closure is still possible but more importantly greater potential yields are required although the chances of accelerating this are discussed and seen to be limited. For all regions, sustainable intensification of cropping, predominantly on existing arable lands, is the best way forward. Combining sustainability with intensification is not a contradiction and is, in fact, essential; sustainability requires the efficient use of all inputs in cropping, and husbandry of the soil and agricultural biodiversity needed to continue to raise productivity. Off-farm environmental impacts are inevitable, but not insurmountable, hurdles. All aspects of sustainability require boosted RD&E and sound rural policies. Greater management skills for farmers and all others involved in crop production are also essential. Contestation based on biophysical aspects of food production and its impacts can be resolved through effective research and development with farmers, while that based on Northern cultural and normative views must not be allowed to obscure the goal of affordable food for all, and reward for farmers comparable with the rest of their societies.

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*Abbreviations:* ACIAR, Australian Centre for International Agricultural Research; CA, conservation agriculture; CAP, common agricultural policy; C3 and C4, two pathways of photosynthesis; EU, European Union; EUE, energy-use efficiency; FACE, Free-air $CO_2$ enrichment; FY, farm yield; GHG, greenhouse gases; IWM, integrated weed management; GE, genetic engineering; GMO, genetically modified organism; NUE, nitrogen-use efficiency; NUEf, nitrogen-use efficiency of applied fertilizer; PUE, phosphorus-use efficiency; PUEf, phosphorus-use efficiency of applied fertilizer; PY, potential crop yield without water, nutrient or biotic stress; $PY_w$, potential crop yield under water shortage; RD&E, research, development and extension; SA, South Asia; SI, sustainable intensification; SIMLESA, Sustainable Intensification of Maize-Legume Cropping Systems for Eastern and Southern Africa; SOC, soil organic carbon; SSA, Sub-Saharan Africa; TE, transpiration efficiency; WUE, water-use efficiency; WANA, West Asia North Africa

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## Dedication

Professor Robert (Bob) S. Loomis (11 October 1928–27 March 2015), Professor of Agronomy[1] at the University of California, Davis, was a crop scientist famous for the breadth and depth of his interests. These ranged from plant tissue culture and basic metabolism, through crop canopies, growth and yield, to cropping and farming systems of North America and the lessons of farming history. Thus he became truly an agricultural scientist, thanks partly to strong links to the mid-west (see Loomis, 1984), where he grew up, and to his wife's home farm in Iowa, and partly to the agricultural ambiance of the Department of Agronomy and Range Science at UC Davis. He combined his broad interest in agricultural systems with a deep understanding of the basic science, the physics and chemistry behind the plant, crop and farm level phenomena (his first degree was actually in physics). He used these skills, along with his pioneering efforts in mathematical and simulation modelling, to quantify underlying relationships driving outputs at higher levels. All this can be seen in his early crop modelling papers (e.g. Loomis and Williams, 1969; Loomis, 1971; Loomis, 1985), his comprehensive review of agricultural productivity (Loomis, 1971) and in the book *Crop Ecology* (Loomis and Connor, 1992; Connor et al., 2011). Our review attempts to honour Bob Loomis's memory by adopting an equally broad view of the science of agriculture, but with our choice of issues and conclusions.

## 1. Introduction

Over the last 60 years or so, agricultural scientists, along with innovative farmers, small and large, have built, by intensification of inputs and capital per unit land area, very productive modern agricultural systems in many parts of the world (Spiertz, 2014). Farmers have adopted and modified new technologies such that crop productivity has advanced spectacularly, with a notable exception being the limited yield progress in Sub-Saharan Africa (SSA), and rainfed parts of South Asia (SA) and West Asia-North Africa (WANA). Problems, some serious, have inevitably arisen as intensification proceeds (see Section 6). In most cases, however, these problems of modernization are being overcome by newer technologies that increase resource-use efficiencies and reduce off-site impacts of agriculture. The important point is that these technologies seek solutions that can maintain the required productivity of agriculture. The cycle should continue so that sustainability, in its broadest sense, is reinforced by this ongoing process of sustainable intensification (SI). Nowhere has there been a need or serious desire, except amongst a privileged few, never full-time farmers, to return to the traditional farming practices left behind.

World population and per capita incomes, and hence food demand, will continue to increase, albeit at a slowing rate, until 2050 and beyond; seemingly only faster economic development and better education of women can humanely slow population growth. Agricultural science remains central to future food supply and to economic development in poorer nations, although alone it is obviously insufficient for the huge task ahead. It must attend to the on-farm technological aspects of SI of cropping in SSA and lagging areas of SA and WANA, by applying and further modifying, techniques and technologies that have been gradually refined in many other countries since the beginning of the second half of the 20th Century. At the same time there is a serious emerging challenge to agricultural science in developed countries where previously substantial yield gains are slowing, while further yield increase is needed to feed huge national populations and/or provide the exports of staple grains that support the food-deficit regions of the world. Crop productivity in developed countries is approaching a threshold that will need a modified paradigm for success at a time when scientific discoveries appear to be advancing with greater rapidity, yet government support for agricultural research, development and extension (RD&E) is declining and the sustainability of modern agriculture is being increasingly challenged by society.

Initially this review will update recent progress in crop yields, guided by the structure and arguments developed at greater length in Fischer et al. (2014). Space forces us to focus on global food production and affordability, primary amongst the various issues currently surrounding the food security debate (including also access, nutrition, health), and we will introduce a novel regional framing of the global agricultural challenge. This will be followed by a discussion of yield prospects across selected global agricultures of today, exploring in particular the future of the intensification paradigm that has been the basis of past progress in global food security. Inevitably attention must be given also to the sustainability of the intensification of input use that this implies. We will present ideas for the direction of future research and development to meet goals when starting from both a low and an already high yield base. We finish with reference to a new wave of contestation that contrasts with what will be an increasingly more complex science-based paradigm for global food supply. The latter forms the crux of our conclusion, in which we see continuing sustainable intensification of the world's cropping systems, involving even more technology and greater management skills, as not only possible but also essential.

## 2. Update on cropping demand and supply prospects

### 2.1. Global perspective

World grain production increased by 227% between 1961 and 2014 (Fig. 1) comprising +161% for yield and a much smaller increase (31%) in crop area, with more than half of the latter coming from increased intensity of cropping on existing arable lands. As a result per capita food availability has improved notably for a population that has risen 141%, and real food prices have fallen overall (Fig. 1).

Looking ahead to 2050, Fischer et al. (2014) concluded that a minimum target linear yield increase of 1.1% p.a. for staple crops (relative to 2010 yields)[2] was needed to hold prices down. Since then, world population projections (UN, 2017) have increased slightly to a predicted median of 9.8 billion for 2050 (31% above the 7.5 billion of 2017, a current rate of increase 1.09% p.a.) but there appears to be lower-than-anticipated expansion in the area of biofuel crops. Thus the 1.1% p.a. conclusion above remains reasonably valid, as does the desirability of lifting that rate to 1.2 or even 1.3% p.a. for greater security. Other estimates tend to opt for even higher yield growth rates (e.g. Nelson et al., 2010) if prices are to be held down, while recent economic equilibrium models deliver such a diversity of projected real prices to 2050 (von Lampe et al., 2014) as to reveal the great

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[1] Agronomy is the science and technology of producing crops. Here, where breeding and agronomy appear in the same sentence, agronomy means crop management.

[2] This projection accepts the inevitability of an increase in net arable area of 0.25% p.a., or 140 Mha between 2010 and 2050.

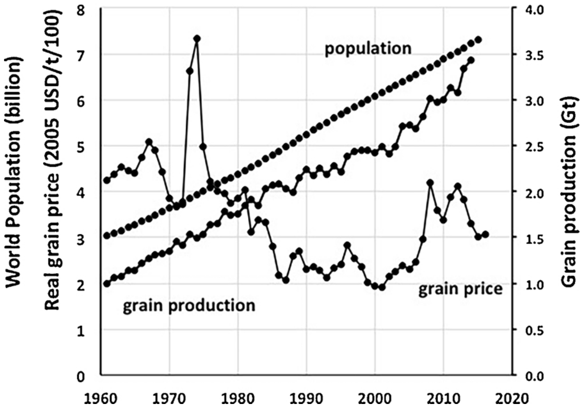

**Fig. 1. World population, grain crop production and real prices of staples for 1961–2016.** Sources: population from UN (2017), crop numbers from FAOSTAT (2017), summing the categories of All cereals, Pulses, and 14 Oilseed (grain) crops; real export prices are the average of wheat, rice, maize and soybean prices (World Bank, 2017).

uncertainty of such exercises. Because population growth rates are steadily declining, the need for the higher yield growth rates will clearly be greatest in the next two decades (e.g., Rosegrant et al., 2013), by which time world population growth is predicted to drop to 0.74% p.a. (UN, 2017 prediction for 2035). Indeed if accelerated progress on food security is not achieved well before 2035, the consequences will already be alarming. For this reason, hereafter we will emphasize the medium term (20 year) perspective for food supply. With this choice, we need spend little time on the issue of climate change and yield, in part also, because it already receives great attention in agricultural research. Temperature change in the next 20 y is uncertain and likely small ($< 0.4$ °C) providing negative warming effects in currently hot regions and positive warming ones in cold regions, plus $CO_2$ responses are clearly positive for yield of C3 crops (about 0.2% p.a.) in both environments (Fischer et al., 2014).

Many scientists (e.g., Loomis, 1984; Loomis and Connor, 1992; Connor et al., 2011; Fischer et al., 2014; Pradhan et al., 2015; van Ittersum et al., 2016) conclude that the preferred way to meet increasing world food demand is to increase crop yield through SI. Crop area increase due to intensification of cropping on existing arable lands is also appropriate but the scope for it is now limited and depends largely[3] on increased double cropping at lower latitudes through net expansion in irrigated areas, something that has slowed markedly (Bruinsma, 2011). Arable land developed for annual cropping currently stands at around 1400 Mha. Increasing crop area by opening new arable lands must be, however, minimized as far as possible because of the huge environmental costs, including biodiversity loss and greenhouse gas emissions, that this would entail (Burney et al., 2010; Tilman et al., 2011). Nevertheless there is suitable new land for arable cropping, up to around 400 Mha, principally in Sub-Saharan Africa (SSA), Latin America and northern parts of Asia (Deininger and Byerlee, 2011). Some is already being developed, mostly in tropical savannahs, where there has been a recent upturn in crop area (Fischer et al., 2014; Grassini et al., 2013); only yield increase on existing lands plus effective regulation can restrain expansion of cropping area. Approximate estimates by Lambin and Meyfroidt (2011) indicate that 2.5 Mha of land is irretrievably lost annually to urbanization and 6.5 Mha to other causes (severe degradation, forestry, parks). If half of these losses were arable land, they would comprise 0.3% p.a. of the existing total of 1400 Mha and be unlikely to slow, thus adding to the imperative to increase yield.

The last 15–30 years or so is a sensible time span over which to assess the current trend in crop yields, balancing year-to-year noise with the need for the most recent measure possible. For the major staples, annual linear growth rates in yield, hereafter abbreviated to FY (farm yield) for clarity, have generally increased slightly in the last 10 years, probably in response to the real price spikes of 2008–2013 and recent low oil prices. Thus the global rates for the four major staple grain crops, retrieved in October 2016 (FAOSTAT, 2017), calculated for 1995–2014 and expressed relative to 2014 yield, were wheat (1.1% p.a.), rice (1.0%), maize (1.4%) and soybean (0.9%). Rapeseed (canola, 1.7%), oil palm (1.5%), seed cotton (1.9%), cowpea (2.3%) and sugar beet (2.2%) reflect the result when a commodity is strongly targeted by researchers (public and private) and innovative producers. The increase in cowpea yield shows what can be achieved by concentrated effort on a previously neglected crop, although possibly assisted by a favourable weather trend in West Africa where the crop is concentrated.

These rates of yield increase for staples may also explain part of the retreat in real grain prices since 2008–2013 (Fig. 1), falling from 120% above the record lows at the turn of the century to only 50% higher in mid-2017 (World Bank, 2017). However there is certainly no room for complacency such as led to neglect of RD&E in the two decades before the price spike of 2008, nor for ignoring the poverty and hunger still existing in many rural parts of the world mired in low crop productivity, nor the world's undernourished population which remains stuck at around 0.8 billion (FAOSTAT, 2017). This persistent hunger is itself reason enough for action, not to mention the greater threat of serious unrest and displacement of people that it and the lack of economic development bring.

### 2.2. *Disaggregating global yield progress and prospects*

Global FY numbers hide great variation within each crop between regions. Across the 35 "breadbasket" cases summarized in Fischer et al. (2014), FY growth rates ranged from 0.2 to 2.8% p.a., all were significantly ($P < 0.1$) positive except three (wheat in France, maize in Italy, rice in Japan). Grassini et al. (2013) studied regional cereal FY change from 1966 to 2010 with diverse functions, and found evidence of recent yield stagnation. Most can be explained by the impact of regulation, for example reducing fertilizer use in parts of Europe, climate trends (e.g. in wheat and maize in Western Europe), or stringent quality demands (e.g., rice in South Korea, Japan and California). Both studies, however, confirmed that the relative rate of yield growth has slowed in recent decades.

It is useful to estimate potential yield (PY) for each crop and region, being defined as the yield obtained with the latest cultivars and agronomy in the absence of water and nutrient limitation and of biotic stress, but otherwise exposed to the climate and natural resources of the region of interest (van Ittersum et al., 2013; Fischer, 2015). A water-limited PY ($PY_w$) can also be usefully defined for rainfed crops. The yield gap is thus PY less the regional FY, that Fischer et al. (2014) argue is most appropriately expressed for food security projections as a percentage of FY. Also the relative rate of change in FY (% p.a.) is the rate of change in PY less the rate of change in the yield gap (which is negative if the gap is closing). This assumes the relative impact of PY progress on FY is unchanged when any new technology associated with PY advance is fully adopted by farmers. Estimates of yield gaps and change rates for the 35 "breadbasket cases" mentioned earlier are given in Table 1, along with the rate of yield-gap closure and of PY progress; PY and PY change estimates were based on yield *versus* date of cultivar release obtained from breeders' trials with disease control and otherwise optimal management. These are side-by-side comparisons so that the estimate of PY progress is not confounded by global $CO_2$ increase (Fischer, 2015).

Crop simulation modelling, in which Bob Loomis was a pioneer, has now become a separate and valuable tool for estimation of PY and yield gaps (van Ittersum et al., 2013). Being based on trial data for model calibration, the modelling results do not differ much from earlier

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[3] An interesting exception is the huge Brazilian cerrado region; much has rainfall sufficient for double cropping.

**Table 1**
**The yield gap and the potential yield (PY) and their relative rates of change for wheat, rice, maize and soybean in 2010 taken from "breadbasket" case studies.** Note: rates of change refer to last 20–30 years to 2010, range to values from the various case studies for estimating mean yield gap and PY or $PY_w$. Source: Fischer et al. (2014).

| Crop (n = number of cases) | Yield gap, % of FY in 2010 | | | | PY or $PY_w$ | |
|---|---|---|---|---|---|---|
| | Mean (%) | Range (%) | Mean rate of change, (% p.a.[a]) | Range in rate of change[a] (% p.a). | Mean rate of change, (% p.a.) | Range in rate of change (% p.a.) |
| Wheat (n = 12) | 48 | 26– 69 | −0.23 | −1.0 to 0.8 | 0.61 | 0.3–1.1 |
| Rice (n = 12) | 76 | 25–150 | −0.39 | −1.5 to 0.6 | 0.78 | 0.3 –1.3 |
| Maize (n = 8) | 104 | 36–400 | −0.61 | −1.8 to 0.7 | 1.08 | 0.8– 1.5 |
| Soybean (n = 3) | 31 | 30–33 | −0.80 | −1.3 to −0.2 | 0.50 | 0.4–0.7 |

[a] Negative change in yield gap means gap closure that is slightly overestimated by about 0.2% p.a. due to the effect of rising $CO_2$ on FY, at least for C3 crops.

estimates (Lobell et al., 2009; Fischer et al., 2014) but the method has been usefully standardized and scaled across regions and countries to give a rapidly growing, up-to-date and valuable global data base, the Global Yield Gap Atlas (see http://www.yieldgap.org).[4] Of a recent flood of modelling estimations of yield gaps, the most valid ones relate to well-defined situations with sound local soil, agronomic, and climate information (Grassini et al., 2015c). Good examples include Kassie et al. (2014) on maize in the Ethiopian highlands, Li et al. (2014) for winter wheat in the North China Plain, Grassini et al. (2015b) with soybean in Nebraska, Aramburu Merlos et al. (2015) covering soybean, wheat and maize in Argentina, and Hochman et al. (2017) for rainfed wheat in Australia.

Table 1 reveals that yield gaps remain large for rice and maize, often exceeding 100%. These large gaps come mostly from low FY for rice in rainfed regions of South Asia and rainfed maize in Sub-Saharan Africa (SSA). For the latter, yield gaps generally exceed 200%, meaning maize FY could be trebled with application of existing technology, something confirmed by the modelling studies mentioned above. Rainfed (and irrigated) wheat in countries of West Asia and North Africa (WANA), not well represented in Table 1, also show very large yields gaps (conservatively greater than 300% according to recent modelling of $PY_w$ for Iraq, Turkey, Tunisia and Morocco (C. Biradar, ICARDA, personal comm.)).

Experience in regions with modern cropping technology suggests that good farmers can achieve FY of about 80% of PY (Lobell et al., 2009), known as attainable or economic yield (Fischer, 2015), implying that the mean yield gap across all farmers is unlikely to narrow to less than 25% of FY. This indeed is now almost the case for wheat in Western Europe, soybean in USA, and maize in Iowa (see later) with estimated gaps in 2010 close to 30% in each case.

Table 1 also presents estimates of the current rates of decrease in yield gap and of increases in PY, both trends that drive FY progress. With the exception of soybean, gap closure has generally been less important for greater FY than has increasing PY, recalling that technology must be adopted faster than it is invented for gaps to shrink. Where gaps are small, PY increase accompanied by farmer adoption of new technology is the only way to increase FY (e.g. soybean and maize in USA, wheat in Western Europe). Where gaps are large (e.g. SSA), yield-gap closure offers huge opportunities to increase FY. While Table 1 warns that yield-gap closure is generally a slow process, experience from the early years of the Green Revolution in Mexico and Asia, when FY was low and gaps very large, point to the possibility of much faster gap closure.

The survey of global cropping from which Table 1 was constructed leads to a useful framing of all global annual cropping into six typologies, here ranked largely by decreasing yield gaps as follows:

1. **Sub-Saharan Africa** (SSA) with many small farmers, low use of inputs, many constraints to modernization both on and off the farm, low FY and very large yield gaps, and rapidly growing imports of staple foods.
2. **West Asia-North Africa** (WANA), but excluding Egypt, with small-to-medium farms, where previously the largely rainfed subhumid landscape supported cropping and grazing livestock. Cropping has been partly modernized but yields remain low, and yield gaps remain moderate to large. There is also large dependence on imported staple foods.
3. **Populous Asia** comprising developing countries with an intensive agriculture dominated by irrigated or humid environments which have been modernizing for the last 50 years or so. Farms are almost exclusively small to very small; FY is moderate to high and yield gaps appear generally only moderate. Egypt is included in this group.
4. **Green Europe** comprising developed countries of Europe, west of the Black Sea, and including the European Union countries and, for evident similarities, Japan, with small-to-medium farms, modern agriculture hence high FY and small yield gaps, but with subsidized farming, and now a growing regulation of agriculture for environmental reasons.
5. **Russia Plus** combining Russia, Belarus, Ukraine and Kazakhstan. It includes exUSSR outside the European Union with many large corporate farms (exSoviet collectivized state and cooperative farms), increasing FY and narrowing yield gaps that are fast approaching those of regions 4 and 6, and has recently achieved major grain-exporter status.
6. **New World** including USA, Canada, Australia, New Zealand, Argentina, Brazil, Paraguay, and Uruguay, with moderate to large, predominantly family farms, and very modern agriculture with small yield gaps and dominant export status.

Other key features of these regions are summarized in Table 2, which *inter alia* show current crop demand and supply based on grouping all food crops (cereals, pulses, oil and sugar crops, roots and tubers) on the basis of their energetic equivalence to wheat, and amounting to 1150 Mha of crop in 2014. Averages are for the 2011–2013 period (central year 2012) because 2013 was the last year for available trade statistics (FAOSTAT, 2017). Notable are the large differences in per capita consumption of crop products, with the high number in the New World boosted about 24% by biofuel and that in Green Europe by 9%, not to mention their large use of grain for livestock-feed also. Of course there are many exceptions and nuances surrounding the six typologies above, including the large number of smallholder subsistence farmers, especially in regions 1 and 3. Nevertheless the system suits the general thrust of this review and its focus on current rates of change in key supply and demand indicators as the best guide to meeting the peak demand growth to be expected in the next 20 years or so.

The challenges are immediately evident in Table 2: the burgeoning

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[4] Readers should note that yield gaps are expressed relative to potential yield in the yield gap atlas and publications derived from this approach. A simple calculation converts this gap to that relative to FY, adopted here because demand and supply projections are also expressed relative to current values.

**Table 2**

**Population, and growth in demand, and supply of aggregated crop products (expressed as wheat equivalents in mass, based on food energy content) across world typologies ranked by decreasing yield gaps and generally increasing cropping intensification.** Principal Sources: UN (2017) for population statistics; FAOSTAT (2017) for Crops. Production values for the FAO groups All Cereals, Soybean, other Oilseeds, Palm Oil, All Pulses, All Roots and Tubers, and Sugarcane and Sugar beet were aggregated after conversion according to food energy content to wheat equivalents at standard harvest moisture content.

| Typology | 1 | 2 | 3 | 4 | 5 | 6 | |
|---|---|---|---|---|---|---|---|
| | Sub-Saharan Africa | West Asia-North Africa | Populous Asia | Green Europe | Russia Plus | New World | World |
| | | **Demand factors** | | | | | |
| Population 2012, billion | 0.89 | 0.49 | 3.86 | 0.67 | 0.22 | 1.00 | 7.13 |
| Population rate of increase 2012, % p.a. | 2.75 | 1.86 | 1.05 | 0.10 | 0.10 | 1.02 | 1.20 |
| Demand increase 2012, % p.a.[a] | **3.57** | **2.43** | **1.71** | **0.18** | **0.59** | **1.22** | **1.58** |
| Consumption 2012, Mt | 280 | 224 | 1514 | 455 | 174 | 872 | 3519 |
| Per cap Consumption 2012, kg/y | 314 | 454 | 392 | 679 | 809 | 872 | 494 |
| | | **Supply factors** | | | | | |
| Production 2012, Mt | 239 | 115 | 1414 | 405 | 225 | 1130 | 3527 |
| Net imports 2012, Mt | 41 | 109 | 100 | 50 | –51 | –258 | |
| Net imports as % Consumption 2012 | **15** | **49** | 7 | 11 | Exporters | | |
| Crop area change 2001-2014, % p.a.[b] | 2.51 | –1.86 | 0.98 | –0.37 | 1.02 | 1.23 | 1.04 |
| New arable land availability[c] | + + + | nil | nil | nil | + + | + + | + |
| Crop yield change 2001-2014, % p.a.[b] | 0.96 | 1.57 | 1.73 | 1.05 | 1.80 | 1.51 | 1.39 |
| Crop production change 2001-2014, % p.a.[b] | **3.26** | **-0.01** | **2.58** | **0.70** | **2.73** | **2.60** | **2.34** |
| Current FY 2012, t/ha[b] | 1.44 | 2.01 | 3.26 | 5.06 | 2.34 | 4.14 | 3.23 |
| Yield gap, % FY | 200–400 | 100–300 | 50–100 | 20–40 | 50–75 | 30–50 | |

[a] This includes population growth plus an estimated effect of growth in per capita income on demand, derived from current per cap income growth (ranging from 1.5 to 4.0% p.a., Green Europe to SSA) and income elasticity for food (ranging from 0.05 (Green Europe), 0.1 (New World) to 0.2 (all others)); numbers are authors estimates guided by Baldos and Hertel (2016).

[b] These numbers are all derived from regression over 15 year period 2001–14, but expressed relative to predicted 2012 values to match the central year of demand estimates. Yield growth in the aggregate tends to exceed that for individual staples give in text because of higher area and/or yield growth rates of high yielding commodities like maize and canola than lower yielding ones like other coarse grains and pulses.

[c] These estimates are based on data from the International Institute for Allied Systems Analysis as interpreted by Deininger and Byerlee (2011). They are mostly supported by the recent land-use multi-modelling effort of Schmitz et al. (2014); + = approx. + 0.3% p.a.

demands in SSA and WANA, as now recognized by many (e.g., Lampe et al., 2014; van Ittersum et al., 2016), and their growing dependence on imports, supplied largely by the New World and Russia Plus. In fact over the last 10 years cereal imports by SSA have increased by 60% and exports from Russia Plus by 75%. Changes in crop area are also revealing, with some losses in Green Europe and worrying ones in WANA, but gains elsewhere. There are good yield gains except Green Europe and SSA, the latter recognized for its reliance on large, but unrewarding, increases in crop area. Crop area increases are surprising high globally (1.0% p.a.), considering earlier comment, and probably cannot be sustained without imposing serious threats to the environment. The effects of yield and area growth are such that growth in world production is actually comfortably ahead of estimated demand growth, but not so in SSA or WANA, although it should be recognized that the income effects included in the demand growth estimates are very approximate. These latter were guided by income elasticities of food demand from Baldos and Hertel (2016) whose equilibrium modelling, perhaps surprisingly, predicts lower real food prices out to 2051. Yield gaps, although they are also only estimates, clearly differ notably between the typologies and establish the boundaries of the ensuing discussion.

## 3. Prospects for typologies with large yield gaps

As Table 2 shows demand increases in WANA and especially in SSA dominate the global challenge to feed the world, and in recent years these countries have been increasing food imports (partly as food donations). Here we concentrate on the more populous and poorer SSA that unlike WANA does not have economic capacity to support continued food importation. The principles of agricultural development to be discussed for SSA are, however, also applicable to WANA, hopefully will be soon when a more peaceful state can be established, and lagging parts of SA.

### 3.1. Using the available agronomic knowledge and revisiting an old paradigm

Fortunately the technologies needed for SI of agriculture in countries with large yield gaps as in WANA are available. We do not accept that these should be cash-free technologies, while recognizing that such technologies can be useful especially in the early stages of modernization (e.g., Pretty et al., 2006). Technologies can follow the pathway of yield increase that developed and transitioning countries have applied and refined since the middle of the 20th Century. These technologies are depicted in Fig. 2, as the pathway of yield increase proposed for ACIAR's SIMLESA aid project in eastern SSA (2010–2018) (www.aciar.gov.au) where subsistence farmers rely for survival on low-yielding crops of maize (FY max. 0.5–1.5 t/ha). $PY_w$ and yield gap for these countries vary from 5–12 and 4–11 t/ha, respectively (Global Yield Gap Atlas, www.yieldgap.org). FY is low because fertility has been "mined" over many years of cropping without nutrient replacement (Craswell and Vlek, 2013). Current average fertilizer application rates to arable

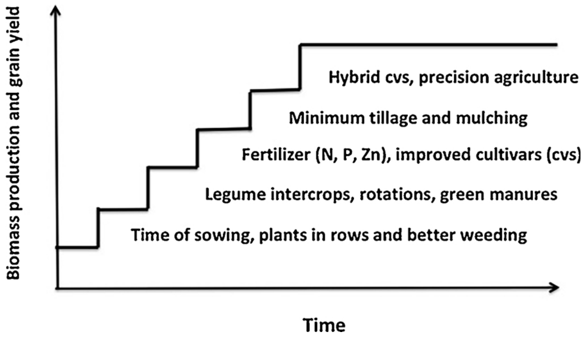

**Fig. 2.** A technology sequence for stepwise intensification of maize production with farmers in Sub Saharan Africa.
Adapted from Dimes et al. (2015).

land are small, 5–15 and < 1–4 kg/ha for N and P, respectively, because many farmers still rely on inadequate quantities of manures, as seen in the fertility gradients decreasing out from homesteads, where animals are kept, to more distant cropping fields.

The objective of the project is to reduce poverty, malnutrition and degradation of soils by diversifying cropping to include legumes, as intercrops or rotations, including green manure crops, with maize and to increase FY of both with fertilizer and improved cultivars and conserve soils by adoption of no-till practices. The process is gradual although initial gains achieved by better weeding and addition of fertilizer (N&P) can be large. These are later amplified by inclusion of improved cultivars selected specifically for adaptation to drought and low-N soils and more fertilizer, P for all crops and (Zn and maybe Mo) for legumes. With improved nutrition, legumes fix more N and their yield provides more valuable and nutritious grain for home use and sale. Productivity increases as farmers develop skill in matching inputs of fertilizer and new cultivars to crop design and planting times, but is achieved only slowly. In this project a technology for mid-late adoption is conservation agriculture (CA), with replacement of tillage by no-till and herbicide in order to retain crop residues for soil cover to increase rainfall infiltration and reduce erosion, and to increase soil organic matter for better water- and nutrient-holding.

This must sound familiar to agronomists reading this essay because it reports nothing new, and was clearly delineated for developing world farmers by Byerlee and Hesse de Polanco (1986) many years ago, reporting stepwise adoption of individual technologies according to their ease, profitability and riskiness. And nor is it surprising for the developed world! Actually it is a summary, contracted in time, of how developed countries have increased FY and reduced yield gaps since the beginning of last century. It is especially descriptive of progress in improvement in crop management and of wheat yields in semi-arid Australia. Cropping commenced there in middle 19th Century without fertilizer leading to a downward trend of yield until early in the following Century when it was reversed by a sequence of technology interventions; fallowing, P fertilizer, legume-based pastures, N fertilizer, weedicides, and throughout by improved wheat cultivars, and subsequently canola and pulse cultivars, better mechanization and no-till, and more recently by connecting farmers via information technology (Connor et al., 2011). Grain sorghum in Australia's subtropics has undergone a similar transformation (Fischer et al., 2014). Now, this suite of technologies and the paradigm under which they were applied are available to agronomists in SSA and countries in similar conditions for application to rapidly and surely increase food production.

For the countries of SSA, generally there is no need to reinvent plant breeding procedures to increase yield or to include disease and/or herbicide resistance of cultivars, no need to discover which nutrients plants require, the importance of micro-nutrients, nor methods to measure their status in plants nor their quantity and availability in soil. No need to discover how to minimize the loss of applied nitrogen; no need to discover that many soils fix P strongly such that responses to applied P improve gradually as the fixation capacity is gradually reduced. And furthermore, this accumulated knowledge and much more, is available in books, or more rapidly through today's worldwide collaborations, on the internet and in specialized *apps* designed to assist management. What is missing most is the willingness to invest in on-farm adaptive research to calibrate responses to local conditions and it is likely that there is less occurring in SSA today than there was 30 years ago. Specific problems in SSA do, however, highlight the need for alert and new crop science including the challenge of dealing with soils so degraded that soil organic carbon (SOC) is less than 0.5% and emerging, and unique, pest problems. The latter include a complex of virus diseases, Maize Lethal Necrosis, not reported elsewhere, and the sudden arrival from the New World in 2016 of the Fall Army worm (*Spodoptera frugiperda*), a highly destructive pest to maize and other crops that is largely controlled in USA by genetically-engineered cultivars.

The advances described above were the result of much research and outreach undertaken sequentially by scientists working under the most well known paradigm in agricultural science – Leibig's Law of the Minimum. This Law advises that the response of a system with multiple inputs is best achieved by identification and supply of the factor currently most limiting. It is a simplification, however, that best explains the success of the stepwise methodology applied in the early stages of SI (Fig. 2) when large yield gains are possible from single inputs (Sinclair and Park, 1993). Later, once these major limitations of soil nutrients are overcome, yield gain proceeds in smaller steps, often to one or more alternative inputs. What provided guidance working with large yield gaps is inadequate once they have been reduced, as we shall see in Section 4 when De Wit's rediscovery of Leibscher's Law is introduced.

### *3.2. The socio-economic barriers*

For developing countries, the relative simplicity of understanding how to increase FY, by reducing yield gaps are matched by seemingly intractable problems for farmers seeking to adopt new technologies. In SSA countries 70% of population live off increasingly smaller and fragmented land areas as rural populations increase, Average land area in the SIMLESA surveys averaged 1–2 ha for Ethiopia, Kenya, Malawi and Tanzania, although 4.7 ha in Mozambique. In all cases, however, average farms combined 2–3 separate plots, generally not contiguous and often up to half-hour walking distance apart, adding to challenges of crop management (www.aciar.gov.au). Many farmers do not have access or cannot respond to market incentives to increase productivity and nor can they afford to leave their land for others to farm for want of rewarding alternative lifestyles in urban areas. Many households that are substantially reliant on off-farm income, often with the menfolk working away in cities and mines while women, children and the old folk work the land, are perhaps more correctly described as part-time rather than subsistence farmers. For them it is a defensible lifestyle decision to remain on the land which unfortunately, from a national perspective, they hold hostage from efficient food production needed for increasing urban populations.

Efficient food production requires technology, inputs and dedication, and larger farms and so must go hand-in-hand with national development of employment for those who wish to improve their lifestyle in occupations other than farming. And there are millions of such resource-limited farmers in developing countries who see only drudgery and unrewarding return to hand labour. Farmers with more land, owned or rented, and more interest to farm more productively in new ways, are the ones who can respond to the opportunities that implementation of new cropping systems offer, provided they have access to cash and/or reasonable credit and that socio-economic conditions are suitable.

The transformation of agriculture into a financially and intellectually rewarding activity provides the opportunity to attract the young back to farming and also to provide other employment activities as service industries in rural areas. Transformation requires more than agronomic viability of new cropping systems, but also establishment of value chains with close integration of farmers and farmers' organizations at the centre between markets for their products and sources of credit for the required inputs together with information and assistance with their use. In risk-prone areas with high rainfall variability, crop insurance schemes are highly desirable. Access to export markets has been a big incentive to development in some areas of Ethiopia and Tanzania. But given all that, the lack of nutrients for crops (fertilizers of guaranteed composition) in quantities appropriate for smallholder farmers at reasonable prices has to be addressed as a critical priority.

Technology and mobile phones connected to the internet can solve some of these long-standing problems in new ways. Small-scale mechanization is now beginning in SSA, 30 years after it began transformation of cropping in Asia. Bangladesh, a land of tiny farms, now has half a million two-wheeled tractors, farming 80% of the arable area (Biggs and Justice, 2015). Information and communications technology

(ICT) is increasingly evident in SSA providing distant farmers with information, advice, access to markets and credit. Many now have smart phones to help them overcome the tyranny of isolation, but distance to the nearest road remains a determining factor in marketing for many farming households. Development of complete infrastructure of roads, transport and communications is essential, as is education for new generations of farmers that agricultural development requires.

This conclusion has been recently reaffirmed by an extensive analysis of household food security at 93 sites in 17 countries in SSA (Frelat et al., 2016). It identified the dominant impact of market access to increases of both animal and crop productivity, leading to the recommendation that “targeting poverty through improving market access and off-farm opportunities is a better strategy to increase food security than is focusing on agricultural production and closing yield gaps” and proceeded to “call for multi-sectoral policy-harmonization, incentives, and diversification of employment sources rather than a singular focus on agricultural development”. We agree with the critical importance of work on market access and value chains but see this as complementary and not as an alternative to agricultural production and closing yield gaps.

The key word here is policy. The development of value chains that link farmers in developing countries to markets; on the one hand; and providers of information; credit and inputs on the other; are needed; such structures are almost taken for granted in developed countries but they also took time to evolve. Given the enormous numbers and diversity of farmers in developing countries the establishment of many local and regional value chains is a large and varied task. Government help is essential but it seems that development of value chains is often slowed by Government policy that maintains control of seed and fertilizer industries and is not well adapted to encouraging agribusiness and the many small-and medium-scale entrepreneurs that the system needs. A recent paper has evaluated the wide range of policy instruments that impact on the scale-out of SI in Ethiopia; Kenya and Uganda (Yami and Van Asten, 2017). The authors conclude that policy support for investment in SI is weak and lacks clear strategies such that farmers are subjected to conflicting advice on such matters as use of fertilizers; tillage and improved cultivars; especially GMOs. They offer suggestions on such matters as the importance of land tenure to enable access to credit to invest in SI; the value of risk insurance; protection for farmers from low quality and sometimes adulterated agrochemicals and genetic material in local markets; and supporting access to improved genetic material while protecting farmers’ rights to existing local landraces.

### 3.3. *The role of irrigation*

The analysis so far reveals the enormous continuing challenge facing SSA to approach self-sufficiency in food production and raises the important question of the potential role of irrigation that is poorly developed in the continent. Region-wide droughts are most common in eastern and southern Africa where irrigation currently depends on dams of small catchments that are prone to periodic depletion. The current focus on increasing FY towards $PY_w$ needs to be supplemented with attention to seeking PY and greater FY in irrigated agriculture where feasible. That irrigation must become part of the solution seems clear. A comparison with previous “green revolutions” identifies the major and consistent contribution of irrigation (Cassman and Grassini, 2013) that caused those authors to ask if the lack of development of irrigation in Africa is an oversight or a response to inadequate water. A detailed analysis (You et al., 2011) concludes that there is indeed substantial potential for the development of small- and large-scale irrigation schemes that could increase food production by 50% in a continent that currently irrigates just 6% of cultivated area (13 Mha) compared to 37% in Asia and 14% in Latin America. MacDonald et al. (2012) confirm that SSA has considerable reserves of shallow ground water suitable for low-cost, small-scale irrigation development. Success will require careful planning, very substantial investment funds depending on the water source and application method, provision for drainage, and good continuing management.

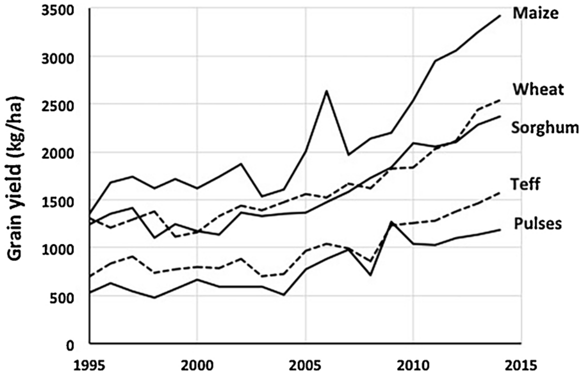

**Fig. 3.** Crop-yield changes in recent decades for key crops in Ethiopia. Developed from FAOSTAT (2017).

### 3.4. *Ethiopia — a potential success story and how to make it so*

Ethiopia is a very poor land-locked, developing country with a population of just over 100 M (80% rural, FAOSTAT, 2017), an increase of 75% in the last 20 years. The cropping systems are very diverse ranging from subtropical to temperate over a large altitude range. Farm size is small (mean size is about 1.0 ha, Lowder et al., 2016). Crop area has increased by 70% since 1995 to reach 12.4 Mha (2014) with contributions from all main crops but especially from cereals (teff, maize, sorghum, wheat and barley, in order of decreasing area). Pulses and oilseeds occupy just 14 and 8% of crop area, respectively. More importantly FY has also increased even more substantially, on average about 120%, but 200% each for chickpea and lentil, 140% for maize, but only 70% for oilseed (Fig. 3). This is spectacular annual yield progress (120% overall is 4% p.a. relative to the 2015 yield) that mostly occurred after 2000. As a result, grain production in 2014 of 23 Mt was 277% higher than in 1995, substantially reducing hunger and poverty (Lenhardt et al., 2015).

Success can be attributed to good government policy and funding directed to resolving constraints to expansion and intensification of cropping. Agricultural spending, on roads, education and extension, is about 15% of the public budget compared to around 3% for the rest of SSA (Lenhardt et al., 2015). The Agricultural Transformation Agency played an important coordinating and catalytic role. Particular attention was given to creating an agricultural extension-innovation-value chain mindset amongst researchers of the Ethiopian Institute of Agricultural Research (EIAR) (Abate et al., 2015) and supporting over 60,000 well-trained extension workers and 9000 multi-disciplinary farmer training centres throughout the country (Lenhardt et al., 2015). The result has been a substantial contribution from agriculture to GDP growth, currently over 10% p.a., and to the reduction of population living on less than US$1.25 per day from 63% to 37% in the 16 years from 1995. Most of the FY increase was due to closure of large yield gaps, for example for maize gaps averaged around 225% in 1988–2007 according to Kassie et al. (2014). There has also been a contribution from CGIAR institutes with improved cultivars of greater PY for most crops, in particular maize, wheat and pulses.

Despite these advances the nation is barely self-sufficient in food and the population continues to grow at 2.5% p.a. Cropping systems, with N use at about 15 kg/ha and P at 5 kg/ha (FAOSTAT, 2017), are dominated by continuous cereals, very little no-till, and a seed system that is not delivering new cultivars to farmers quickly enough. There are, however, good prospects and climatic potential to continue increase in FY, along with diversification into higher value pulses and oilseeds, some with export opportunities. This gives room for optimism for what was one of the world’s poorest nations 25 years ago, provided the Government of Ethiopia and the EIAR can hold to the successful pro-agriculture policy settings.

### 3.5. Conclusion

The agronomic and socio-economic technologies, skills and pathways are established for regions with large yield gaps so that, with sufficient funding and home-government support, it should be possible to make rapid progress in adoption of SI to greatly increase food security in SSA, as we have seen in Ethiopia. Success will require the local adaptation of cropping system research to provide a suite of tailored modern cropping technologies for yield-gap closure and greater FY now; increases from greater $PY_W$ can be a later objective. As Giller et al. (2017) recently argued we need to move from principles of agronomy to placed-based agronomy. More difficult, however, is the challenge to develop infrastructure and institutions for the myriad value chains that millions of farmers need for the financial incentive to adopt new cropping systems. Transformation can be achieved in stages. Initially, linking farmers in cooperatives to achieve a critical land area and bargaining power for purchase of inputs, sharing of machinery, sale of products and access to a larger market. But ultimately it will require amalgamation of small intrinsically inefficient farms and therefore provision of alternative opportunities for those farmers who leave agriculture. In part this can be provided in rural areas, for those with skills, by employment in support industries for agrichemicals and machinery. This is a particular option for those youth who see an opportunity for a beneficial lifestyle and are willing and able to undertake technical training.

While some countries are better endowed than others to increase crop production sufficiently faster than population growth to secure food security, for others the challenge may be unachievable (van Ittersum et al., 2016). An option can be found in the development of irrigated cropping that has the potential to substantially increase food production without the need to increase cropping area, but the investments needs for irrigation are very substantial.

## 4. Prospects for typologies with small yield gaps (groups 3–6)

### 4.1. Introduction

There are three cropping regions with relatively small yield gaps, defined here (30–100%), that fall usefully into the last four earlier-mentioned distinct typologies (Table 2). All have undergone considerable intensification in the last 30–100 years.

- The most important for feeding the world is Populous Asia, comprising East, South and South-East Asia. There, yields of irrigated wheat, rice, maize and many minor crops have steadily increased during 30–50 years of modernization. Rainfed crops, such as non-irrigated rice, however lag somewhat. Net food imports are significant, being dominated by feed-grain imports by China including those to accommodate changing human diets, but are small relative to consumption and the region's economic ability to pay. This region suffers high levels of atmospheric pollution with aerosols and ozone.
- Green Europe forms the next distinct grouping, dominated by the European Union, where diverse cropping under mostly humid conditions has modernized largely under the stimuli and controls of the Common Agricultural Policy (CAP), leading to generally high yields, slowing yield progress and small yield gaps.
- Finally we have the two crop-surplus exporting regions, Russia Plus and the New World. Cropping is under both humid and sub-humid rainfed conditions dominated by wheat, maize, soybean, and oilseeds. There is a long history of modernization in the New World and generally small yield gaps. Russia Plus had begun to modernize under the USSR, but then suffered the upheaval of de-collectivization. Crop yields are now growing strongly but yield gaps are probably still greater than in the New World.

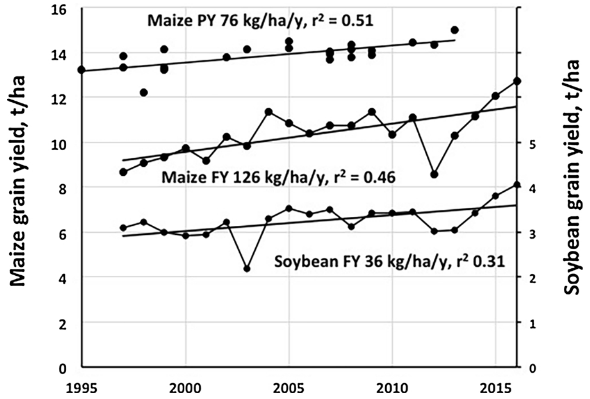

**Fig. 4. Time trends of average farm yield (FY) of maize and soybean, and potential yield (PY) of maize, in Iowa.** FY from NASS, USDA (2017); PY from 2013 and 2014 trials of DeBruin et al. (2017).

In this section we will attempt to look across these four typologies, while recognizing that only in Green Europe and USA are some yield gaps close to the economic minimum (25–30% of FY), such that yield-gap closure remains an option elsewhere. But we begin by highlighting yield progress in Iowa (Fig. 4), an agro-climatically favourable representative of the New World, and the beloved home state and agricultural real-world anchor for Bob Loomis. Iowa has been the target of huge investment in public and especially private agricultural RD&E, and much agricultural intensification during the last century.

In Iowa most maize is grown in rotation with soybean: 77% of maize followed soybean and 93% of soybean followed maize in the recent comprehensive Midwest study of Seifert et al. (2017). FY continues to grow, at 1.1% p.a. of current FY for maize and 1.0% for soybean. PY for maize is also increasing, although more slowly at only 0.5% relative to the latest released hybrids (Fig. 4, 14.5 t/ha in 2013) so the yield gap then was only 28%, having shrunk from 43% 20 years earlier. Soybean PY appears to be growing at 0.7% p.a. (Rincker et al., 2014), and its yield gap is around 30% or less (Fischer et al., 2014). These authors and Grassini et al. (2015a) discuss the drivers of these FY increases. Steadily improved maize hybrids and soybean cultivars (now both > 90% GE for herbicide and insect resistance) interact positively with many management improvements, such as earlier planting, regular intra-row spacing, and better seed quality and seed dressings, and including higher plant density for maize. Fertilizer rates appear to be steady at around 160 kg N/ha for maize, and 23 kg P/ha (maize) and 7 kg P/ha (soybean). Lately a period of good grain prices (2011–2013), a major drought (2012) and an outstanding season (2016) have added to the mix, along with an intriguing study (Tollenaar et al., 2017). These authors argue that maize yields (both FY and PY, and presumably for soybean also) in the corn belt have been increasing at about 0.3% p.a. due solely to "brightening" of solar radiation by a similar proportion since the mid 1980s, likely because of control of aerosol pollution.[5]

Of course Iowa, nowadays a landscape of moderate to large family cropping enterprises, represents an extreme of intensification, and it has its challenges, for example, with nitrate pollution of waterways (see later). Further progress will be closely linked to increase in PY, the subject of the remainder of this section, and this is also the case for situations with somewhat larger gaps, although still small by world standards.

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[5] If this is correct as seems likely, the implications for heavily polluted South and East Asia are heartening.

### 4.2. Raising PY (and $PY_w$) through breeding

Table 1 reports estimates of PY (and $PY_w$) progress that are relevant to this discussion. To the global average rates shown for wheat (0.6%), rice (0.8%), maize (1.1%) and soybean (0.5%), other values can be added from the same source for cassava (1.5%), canola (1.4%), sunflower (1.0%) and barley (0.7%). These annual rates relative to the most recent cultivars released are declining not only because PY is rising but also because, as almost all breeders will admit, progress is becoming more difficult, especially with the staple crops. There is as yet no sign, however, of an end to PY progress, nor is the relative progress in $PY_w$ less than that in PY. But there is a tendency for hybrid crops to show greater rates of progress, probably because of larger investments in breeding them by the private sector. Gains were greatest in maize, where the absence of quality requirements aided breeding for yield, but after almost a century of progress even this has slowed (e.g. now only 0.5% p.a. in Iowa).

Fischer et al. (2014) attempted to take a balanced look at PY (and $PY_w$) prospects that could involve both new cultivars or new agronomy or their commonly positive interaction. For breeding, the single important negative is the diminishing return (progress per unit of financial investment) mentioned previously, but there are various positives in:

- a host of new breeding technologies including molecular markers and culminating in genomic selection (e.g., Bernardo, 2016),
- steadily more efficient and accurate phenotyping under the general banner of high throughput phenotyping (e.g., Araus and Cairns, 2014),
- crop simulation models and weather and soil databases that permit quantification of environmental patterns to support breeding (Chenu, 2015), and unprecedented, if poorly validated, exploration of gene to trait to yield relations (e.g., Hammer et al., 2005; Chenu et al., 2009),
- considerable unexploited genetic material safely stored and increasingly well documented in the world's gene banks, and
- for some crops there remains the possibility of a modest one-off yield boost through commercialization of F1 hybrid seed (e.g. wheat).

Not included in this list is genetic engineering (GE) for greater PY, because to date no such cultivars have been released with higher intrinsic PY (and only one case for higher $PY_w$, in maize (Nemali et al., 2015)). For several reasons we consider the target too difficult for impact in the next 20 years, notwithstanding the repeated claims of imminent success. This view is supported by the thorough review by Hall and Richards (2013). It should be noted, however, that GE has indirectly and modestly increased FY via better insect and herbicide resistance (Klümper and Qaim, 2014). This is mostly one-off yield-gap closure, but with enduring environmental and financial benefits.

A major part of future of breeding for greater PY relates to those yield-enhancing plant and crop traits still amenable to change through breeding. This has been widely discussed by crop physiologists (e.g., Foulkes et al., 2009; Reynolds and Langridge, 2016) and in Fischer et al. (2014). Greatest emphasis is currently being placed on increasing carbon gain (biomass) through increasing leaf and canopy photosynthesis, and hence crop radiation-use efficiency. As harvest index generally approaches quite high levels in most crops (around 0.5 for grains, 0.7 for roots and tubers), there are sound precedents for the biomass approach, some arising unwittingly from past progress, and this is the very area of crop physiology to which Bob Loomis contributed much. However, to date planned delivery of traits for higher biomass, whether via natural genetic variation or GE, has been minimal. Biomass can also be increased by extending crop duration and the period of light capture, but in most PY situations this is already close to the seasonal limits set by low temperature or water supply. However a few possibilities do still exist, as illustrated by attempts to breed sugar beet adapted to late autumn planting. The crop is typically planted in spring at latitudes of 40–45 °N, whereas for autumn planting it must survive winter freezing and not be triggered to flower by vernalization during that time. If this could be achieved, sugar beet should develop more leaf area sooner in the spring, deeper roots to exploit water and nitrate, and produce more biomass and yield by harvest in the following autumn (Jaggard et al., 2010).

Under water-limited conditions $PY_w$ has definitely improved even recently relative to crop evapotranspiration (ET) (e.g. wheat in Australia, Sadras and Angus, 2006). This could partly be the spill over of PY progress that can be expected in most situations other than under extreme water shortage. At the same time, traits specifically targeted to improve performance under water shortage have received much attention from physiologists over a long period. Some have probably been exhausted by breeding (e.g. earliness) while others remain to be thoroughly validated in the field (e.g. deeper roots, tolerance of grain setting to reproductive stage drought) and then converted into usable selection criteria. Others are unlikely to ever leave the glasshouse.

There does, however, seem to have been some significant progress in seeking higher transpiration efficiency in wheat (Richards et al., 2002), deeper rooting in rainfed rice (Venuprasad et al., 2008), and especially with targeted selection for drought tolerance in maize (Edmeades, 2013). One trait recently gathering interest in some rainfed crop species, and of possible value to others, is stomatal sensitivity to vapour pressure deficit (vpd) for which genetic variation has been found in many crop species (Vadez et al., 2014). It appears that some genotypes restrict the expected linear rise in transpiration with increasing vpd at some moderate-to-high threshold, thereby conserving soil water ahead of critical reproductive events to the benefit of yield, especially if rains falter and then return. This mechanism appears to be the basis for success for a new suite of Aquamax® maize hybrids that exhibit modest yield gains (6%) under water shortage across the US Corn Belt (Gaffney et al., 2015).

Concluding this brief discussion of breeding and PY prospects, one cannot be very optimistic about a boost in the current rate of breeding progress. The transformative changes so frequently heralded, such as a breakthrough for example in photosynthesis, are likely to take a long time to impact on PY and FY. At best we can hope that breeding and new agronomy (see below) will maintain current rates in the range of 0.5–1.0% p.a.

### 4.3. New agronomy and breeding x agronomy interactions for greater PY ($PY_w$)

New agronomy is a part of overall PY increase, commonly in the past interacting very positively with breeding, such that most studies conclude both have contributed more or less equally to past PY (and FY) increase. It is difficult to say whether breeding has led this or if agronomy has been the driver, but close communication between the two has been essential for its realization. In maize, however, the highly positive G x density interaction may come to an end when densities are high enough to maximize biomass production in the available crop cycle. At today's 80,000 plants/ha in Iowa that is not to be far away from maximum densities of 100,000 plants/ha as used in New Zealand. There may, however, remain some scope for further PY gains using more regular planting arrangements (e.g., triangular or honeycomb designs) that minimize early interplant competition. Such precision planting is possible via seed singulation (precisely spacing individual seeds along the row), but has yet to be widely explored in maize or other field crops and will likely require new plant types from the breeders for greatest gain. Curiously, rice production in Asia (apart from that in the System of Rice Intensification) is proceeding in the opposite direction as increased labour costs mean that direct seeding in rows replaces transplanting on a typical 20 × 20 cm grid. In this case it is unclear if current cultivars are the best adapted to the new planting system.

More generally, it seems that new opportunities for yield increase and/or for positive interactions with new genotypes keep emerging in agronomy. Conservation agriculture (CA), in particular in subhumid regions with fallow periods, has generally provided significantly more stored soil water at seeding and hence higher $PY_w$ in any given region. In the Great Plains of North America this has actually led to shorter fallow periods that allow additional crops in the rotation. In this case $PY_w$ of individual crops may suffer but cropping intensity and overall average annual system production increases, as has happened in for example Saskatchewan with a general shift away from one crop every second year (after “summer fallow”) to a crop every year. In southern Australia CA has increased soil-water storage creating opportunities for earlier sowing of wheat in autumn. This in turn demands new cultivars with appropriate phenological development controls (sensitivity to vernalization rather than to photoperiod), and brings prospects of greater grain yield (Flohr et al., 2018), and of extra winter forage in grazing-grain enterprises. CA is at the early adoption stage in Asia bringing many new challenges, especially proper herbicide use and mechanization suitable for small-scale farmers. It primarily offers water and fuel savings, but can also offer significant increases in potential yield of wheat from earlier sowing, again requiring new cultivars, and also facilitating increased intensity of cropping (Hobbs et al., 2017).

Other agronomic innovations that may lift PY concern soil management. Understanding of soil microbiology has been boosted by the advent of molecular tools and this new knowledge may eventually lead to positive impacts on yield additional to those already exploited through *Rhizobium* biology for legumes, mycorrhiza management for some crops, and crop sequencing. It may, however, turn out that soil chemistry and physics have more to offer than soil biology. Already PY of the Brazilian cerrado soils has been lifted more than two fold with massive doses of lime and phosphorus. Other such one-off boosts to productivity are seen with tile drainage, and in rainfed environments such as Australia, amelioration of coarse topsoils with addition of clay (“claying”), or heavy topsoils with gypsum, and of heavy subsoils with ripping and deep placement of lime and organic materials. It is a moot point whether such major investments in the natural resource base of cropping represents an increase in PY rather than yield-gap closure. To the extent that the prior condition was not recognized as lacking a manageable (and profitable) input (e.g. lime and P in the case of the cerrado), its initial recognition is clearly PY increase. Once the improvement is recognized and adopted by some, it becomes gap closure for the non-adopters. In all cases potential yield is lifted. There is much evidence that soil compaction can restrict root penetration and PY, and in addition, the occasional outstanding performance of crops in “loose” soils (Fischer et al., 2014) deserves follow up. Precision guidance and controlled traffic can restrict compaction to a small fraction of any field.

Developments for crop agronomy from outside of agriculture could include improved short term and seasonal weather forecasts. Risk aversion especially in subhumid rainfed environments encourages farmers to reduce inputs (e.g. N fertilizer) to avoid losses, thereby forfeiting yield gains possible in years of good rainfall. Better forecasts, for which there are reasonable prospects (e.g. Klemm and McPherson, 2017; Rodriguez et al., 2018), bring the possibility of lifting PY or $PY_w$. Another potential “left field” development is the use of ultra-thin biodegradable plastic films, sprayed between crop rows to increase soil warming in spring at higher latitudes or to reduce soil evaporation in low rainfall locations. Already plastic film is widely used for this purpose in rainfed cropping in northern China, with large benefits to yield, but its low biodegradability renders the practice environmentally unacceptable.

Finally, it should be noted that agronomy extends beyond individual crops to cropping and farming systems, involving crop sequences and the inclusion of grazing and stall-fed animals. There may be benefits to system productivity with crop rearrangements (Guilpart et al., 2017), or to individual crop PY, in particular from breaking continuous monocultures and binary rotations of wheat, maize or soybean with different crops such as the oilseeds and pulses, or pastures. This is discussed under sustainability (Section 5).

### 4.4. The new paradigm for closing smaller yield gaps

Situations with yield gaps between 100% and 30% can also of course benefit from activities targeting yield gap closure. Fischer et al. (2014) cite many cases where recent crop management advances have closed yield gaps at the sort of rates shown in Table 1; in the Iowa maize example (Fig. 4) the yield gap was closing at 0.6% p.a., the difference between FY and PY rates of progress. The now common situation in regions with smaller yield gaps of multiple simultaneous constraints in cropping is perhaps best understood through de Wit's rediscovery of Liebscher's Law, or the Law of the Optimum (de Wit, 1992).[6] This Law explains how the response to an input in agriculture is maximized when all other inputs are optimized. A simple example is seen in the positive interaction between N and other inputs in many situations, such as more grain produced per unit added N when P is supplied in P-deficient situations or microelement deficiencies are alleviated or water is supplied in dry situations. The principle also applies when yield targets rise in response to non-nutrient inputs such as the climatic potential of the environment (as determined largely by solar radiation and temperature), or greater PY of a new cultivar (as determined by its genetics), and more skilful management. However, Lobell et al. (2009), commenting on the lack of persistence across years of inter-field variation in irrigated wheat FY in the Yaqui Valley of Mexico, concluded that chance is also an element in input management. It arises because weather departures from the average, currently almost impossible for the manager to anticipate, may change the optimum management strategy for any given year (e.g. the optimum sowing date or fertilizer rate or cultivar to plant). The challenge for the future therefore is find ways to apply this paradigm to increase yield when individual gains are small, so difficult to identify under field conditions, and the wrong decision is more likely to have negative impacts; obviously better seasonal weather forecasts have a key role to play in this.

## 5. Cropping intensification and natural resource-use efficiency

Implications of natural resource-use efficiency and sustainability deserve attention because some have argued, we consider erroneously, that intensification of cropping inputs can neither be resource efficient nor sustainable, that SI is an oxymoron. Natural resource-use efficiency in cropping refers to yield-scaled efficiency (output/input) with which water, nutrients and energy are used to produce food. These also relate to Sustainability (Section 6) in so much as these natural resources are limited in supply. The subjects are discussed at length in Nösberger et al. (2001), Connor et al. (2011), Fischer et al. (2014) and Wezel et al. (2015), and only key aspects are briefly highlighted here.

### 5.1. Nutrient-use efficiency

In applying SI to cropping, the aim is to optimize all resource inputs according to Leibscher's Law (Section 4.4), or to equalize marginal productivities of limiting factors in the terms of Sinclair and Park (1993). This is well illustrated with nitrogen-use efficiency (NUE) in USA, that in terms of nitrogen fertilizer use efficiency (NUEf) has been steadily increasing in USA since 1970 even as N rates have risen (Fig. 5). Increased PY through breeding and planting density and the proper supply of other nutrients, along with other improved management inputs already mentioned, have countered the diminishing returns that result when N is increased while other inputs are held constant.

Bob Loomis frequently observed that use-efficiency analyses in general require careful measurement of all inputs and outputs of the

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[6] Incidentally de Wit was an early visitor to the Loomis laboratory in UC Davis.

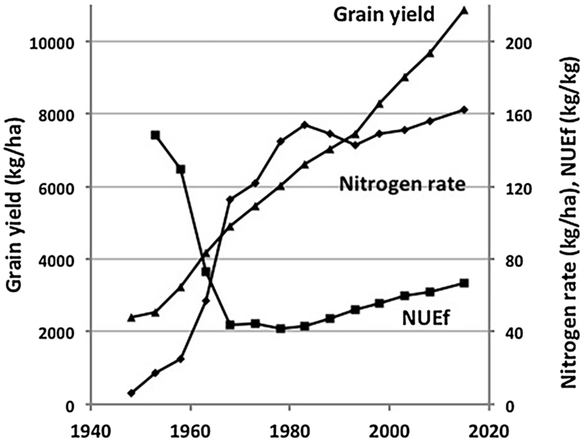

**Fig. 5. Change from 1945 to 2015 of maize grain yield, N fertilizer rate on maize planted area, and the ratio yield to fertilizer N (NUEf) in USA.** Average of 5 year intervals plotted against middle year, but final point (2015) is average of 2014 and 2016 only, because there was no N use data available for 2011–2013.
Source USDA (2017).

resource being considered. In the same vein, Lassaletta et al. (2014) have recently argued that Fig. 5 is incomplete, because fertilizer (and native soil organic matter) are not the only sources of N. There are also possibilities of N input from manure, biological N fixation (symbiotic and non-symbiotic), and from atmospheric deposition (and irrigation water). For the maize example of Fig. 5, manure and deposition are small and likely to have declined over time (Fischer et al., 2014), irrigation is relatively insignificant, while non-symbiotic N fixation although potentially significant (Ladha et al., 2016), is again likely small. On the other hand, maize is usually grown in rotation with soybean and the ratio of soybean to maize area in USA has gradually increased between 1970 and 2010 (from about 0.8–1.0), the net contribution to the system from N fixation by high-yielding soybean needs to be considered. Doing so, a recent meta-analysis by Salvagiotti et al. (2008) established the contribution as a mean of −40 kg N/ha (25–75% range of −4 to −64 kg N/ha), commonly therefore a small loss arising because the proportion of fixed N in soybean biomass in these systems is between 50 and 60% which is less than the N extracted in grain. Thus it appears a more thorough analysis of N use and US maize yield change does not challenge the general principal enunciated above by de Wit.

Lassaletta et al. (2014) also evaluated country level NUE (meaning in this case N output as a% of N input, across all inputs and all crops) and give several examples of recent NUE improvements as N inputs have risen (USA, Brazil, Bangladesh). Several European countries where stronger regulations may now be influencing N management also show rising NUE (e.g., Greece, France and Netherlands). USA, Greece and France are currently each running at about 65% efficiency. In India and China, on the other hand, this ratio is low (30%) and still declining; unnecessarily high fertilizer price subsidies are likely a factor in these cases. And finally it appears that high NUE can arise in some countries where soil mining continues (e.g. Nigeria), as was seen in Fig. 5 in the early years of maize cropping in USA.

Many possibilities exist for managing N fertilizer more efficiently in terms of the right source, timing, amount and placement, so as to increase the proportion actually taken up by the crop. Improved management needs skilled farmers, price incentives, more targeted research, and effective regulation. Plant breeding has also improved N-uptake efficiency, and may do even better with the exploitation of traits such as biological nitrification inhibition discovered in the tropical grass *Brachiaria* (Subbarao et al., 2013). Finally breeding has raised N-utilization efficiency in staple crops (grain per unit N uptake, kg/kg). Greater grain yield can now be achieved without greater N uptake because breeding has changed the biological limits, as determined by the N concentration in the product and the N harvest index. In conclusion further improvements in NUE can be anticipated.

The situation with respect to phosphorus-use efficiency (PUEf, grain produced relative to P fertilizer applied) is similar to that for N, with two key differences. First, available P from added sources (fertilizer or manure) is fairly rapidly rendered only slowly available in soil due to fixation into relatively immobile inorganic and organic forms (Sattari et al., 2012). Second, P losses from cropland, apart from product removal, are a small part of the P balance, although they can be environmentally damaging. PUE has become topical because of reports of looming shortages of fertilizer P, but these are without foundation (Scholz and Hirth, 2015). For agricultural science the issue remains one of improving PUEf, because P is an expensive input to cropping, and it is imperative to use as much P as possible from waste sources (manure, sewage) as circumstances permit. PUEf (again grain produced relative to fertilizer P applied) has generally improved as cropping has intensified (examples in Fischer et al., 2014) partly for the same reasons given for NUE improvement, and partly because the P-fixing capacity of soils has become saturated following years of P fertilizer at application rates that, although tempered by economics, were well in excess of the P removed in crop products. Thus efficient P-fertilizer management also follows well researched rules also relating to source or form, amount, and placement, sometimes deep placement for greater availability, but timing is inflexible, usually restricted to incorporation at seeding. The optimum amount of applied P is best determined by soil test and relates to building up to, and maintaining but not exceeding, an appropriate critical available P level over the years (Roberts and Johnston, 2015). Once this has been achieved, P fertilizer rates should fall to maintenance levels, balancing additions and removals, as has happened in Western Europe (Sattari et al., 2012). In contrast P input to crops in China has substantially exceeded P removal since 1970 so that amounts now used likely well exceed those needed for maintenance, offering the possibility of large savings of fertilizer (Sattari et al., 2014). At the other extreme SSA, where P content of soils is generally highly depleted, faces low PUE due to fixation of much of any P applied. For example Kamanga et al. (2014) report PUEf values around 80 kg grain/kg fertilizer P in maize in Malawi when P applied was 9 kg/ha and N deficiency and weeds were removed. In USA, PUEf of maize is around 400 kg/kg due application of P at maintenance rates.[7]

With a view to lowering P-fertilizer needs, plant breeders, struck by variation in PUE between crop species often arising from differences in P-uptake efficiency, conditioned by soil pH and P and aluminium levels, continue to seek PUE variation within species. Theory and evidence links intraspecific variation in P-uptake efficiency to variation in root proliferation in the topsoil, root hair length, propensity to host mycorrhiza, and root exudates that dissolve less available forms of P (Richardson et al., 2011). However, the impact in terms of released cultivars specifically bred for high P uptake efficiency is as yet minimal (Van de Wiel et al., 2016). It must be remembered that additional roots or root exudates have a metabolic cost to the plant, and that traits that are facultative and only expressed when soil available P is low, may be of no benefit at optimal P levels. As with N, P-utilization efficiency has increased gradually with breeding for higher PY (examples in Fischer et al., 2014), while deliberate selection for low grain-P concentration has often been proposed to increase this further.

### 5.2. *Water-use efficiency*

As is common but not universal, crop water-use efficiency (WUE, kg/ha/mm)[8] is defined here as grain yield produced per unit of crop

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[7] Note that it is the marginal PUE which determines the economic P rate, not PUEf which is also known as the partial productivity.

[8] Others call this water productivity (e.g., Yadvinder-Singh et al., 2014). Note 10 kg/ha/mm equals 1 g/kg or 1 t/megalitre or 1 kg/$m^3$.

evapotranspiration (ET, sowing to maturity). Improvement in yield and WUE in rainfed cropping (e.g., Sadras and Angus, 2006) is not specifically discussed here because the opportunity cost of this water is close to zero, since it has limited other uses as a natural resource, being otherwise lost as evaporation and weed transpiration. On the other hand, water used for cropping under full or supplemental irrigation currently utilizes 70% of global water extracted by mankind from streams, rivers and aquifers, and is threatened by competing users, over extraction of aquifers, growing demand for environmental flows, and climate change (Elliott et al., 2014).

It is in irrigated cropping that WUE becomes a key natural resource issue. There, other definitions of WUE often arise, ones which cover losses between irrigation water supplied to the field and useful crop ET (e.g., evaporation of water used in land preparation, water left in the soil at maturity, and runoff and deep drainage due to over irrigation, poorly levelled land, and/or unanticipated rain). For irrigation engineers water supply means the water leaving the stream, aquifer or reservoir, which can be subject to additional major losses, often exceeding 50%, depending on distance from source to field. Some such losses such as evaporation, weed transpiration and drainage to salty water bodies, are permanent, others such as drainage to aquifers or other streams are not, and so need to be distinguished. This whole system picture is essential for a complete analysis of water consumed by irrigated cropping (Hsiao et al., 2007; Fereres et al., 2017) and considerable scope exists for increasing water-use efficiency at the system level, but further discussion here is confined to WUE as defined above.

Improvements in irrigated cropping that increase yield also raise WUE by either maximizing crop transpiration as proportion of ET (e.g. minimizing soil evaporation with cover from crop residue and with rapid early growth), or maximizing transpiration efficiency (TE, dry matter (DM) production per unit transpiration), or maximizing HI. For example in a long-term experiment with irrigated double-cropping of wheat-maize in the North China Plain during 1980–2009, Zhang et al. (2011) reported that WUE increased by about 60% (to reach 15 and 22 kg/ha/mm for wheat and maize, respectively). At the same time annual grain yield increased by 100% (from 8 to 16 t/ha) with better cultivars and agronomy (e.g. no-till with residue retention). Grassini et al. (2011) recorded average on-farm WUE values for grain for aquifer-irrigated maize in semiarid Nebraska of 19 and 32 kg/ha/mm (flood and sprinkler irrigation, respectively), and predicted that this could be raised further to 42 kg/ha/mm under sprinkler irrigation by eliminating excess watering with better forecasts, deeper rooted hybrids, adopting no-till and residue retention, and rotating maize with soybean. The role of no-till and direct seeding for increasing WUE in irrigated cropping in the Indo-Gangetic Plain is also noteworthy (Yadvinder-Singh et al., 2014). In summary marked improvements in WUE are possible and generally involve very skilled management, accurate weather forecasts, and the complete control over water supply that on-farm tube wells permit.

The highest WUE values for irrigated maize in Nebraska come close to the current biological limits imposed by TE and HI of the best maize hybrids (Grassini et al., 2011). Furthermore TE, the terms of water trade for dry matter production, is strongly and inversely related to the prevailing vpd. Recent estimates are summarized in Connor et al. (2011). The crop physiological research frontier currently focuses on raising TE, but several issues remain moot: is leaf level TE, as measured in a cuvette, indicative of canopy TE and can leaf TE be raised without sacrificing photosynthetic rate? This is relevant because recent genetic progress in PY has generally been associated with increased stomatal conductance in C3 crops (Roche, 2015),[9] and increased photosynthesis but reduced TE at the leaf level. Space precludes further discussion of the leaf-to-canopy question, suffice to say that results where crop ET has been measured carefully suggest that genetic increases in stomatal conductance have much smaller relative effects on canopy T because of the limited "coupling" between dense crops and the atmosphere (e.g. Pinter et al., 1990; Shimono et al., 2013, Fereres et al., 2014) and may not even reduce canopy TE (Iwaka et al., 2018). In addition it should not be forgotten that the greater transpirational cooling from high stomatal conductance may have direct benefit for yield formation in some irrigated crops like cotton in hot locations (e.g. Lu et al., 1994).

### 5.3. *Energy-use efficiency*

Energy-use efficiency (kg grain or grain equivalent per GJ total energy input, EUE) is a controversial index because a range of energy sources (human, animal, hydro, fossil fuel, nuclear) is used to produce the singular human dietary energy. While alarmists raise concerns over the growing reliance of cropping on non-renewable fossil fuel it is a less important issue to sustainability than the supply of either water or nutrients. Alternatives to fossil fuel energy will become available and will be used as needed in agriculture to maintain the efficiencies of productivity of other current inputs and importantly to reduce the drudgery.

Loomis and Connor (1992) broadly review the use of energy in agriculture, and point to the folly of low energy-input farming, as proposed at that time by energy fundamentalists, and with Fischer et al. (2014) summarize effects of cropping intensification on energy-use efficiency (EUE), measured here as kg of grain per GJ of total energy use. Both sources list many individual input-energy costs.[10] Assessing energy consumption involves a full life-cycle analysis of inputs, including the embodied in energy inputs themselves (petrol, diesel, electricity), and also the energy requirement of farmers themselves. Accounting for the human labour input is essential when traditional and modern systems are compared. While the energy requirement of a subsistence farmer may be taken as the required 12.5 MJ/day of dietary energy, the embodied energy of today's average modern farmer has an additional 600 MJ/day. Even so there is considerable energy saving in modern compared with subsistence agriculture. The energy cost for a subsistence farmer digging 1 ha to 20 cm depth in 150 days would be around 1.9 GJ. In contrast, a modern, mechanized farmer achieving the same in 1 h with a medium sized tractor would incur a total energy cost of 1.0 GJ (24 L diesel fuel plus energy embodied in machinery) plus a small dietary and embodied energy cost around just 75 MJ.

Energy efficiency calculations need to be scrutinized closely for omissions and basic assumptions, but it is clear that, despite increasing total energy input per hectare with modernization, yield has increased relatively faster, and EUE for grain has increased. US maize production is a frequent target for popular criticism, but over the whole country, EUE increased by 25% from 1987 to 2007, to reach 450 kg/GJ (Keystone Center, 2009). For supplementally irrigated maize in Nebraska in 2005–2007, Grassini and Cassman (2012) recorded a massive energy input of 30 GJ/ha, dominated by ground water pumping (42%), nitrogen fertilizer (32%) and grain drying (9%). Even so average EUE was 440 kg/GJ and the best managed crops exceeded 525 kg/GJ (total energy output to input ratio of 8). Biocides are energetically expensive (around 350 MJ/kg a.i.) but they only contributed 3% of the total energy inputs because of the small amounts used. Many studies of modern cropping find N to be the largest energy cost, and one reason for the increase in EUE over time has been the doubling since 1950 in efficiency of $NH_3$ manufacture in the Haber-Bosch process, that is only now is reaching theoretical limits (Smil, 2001). Legume cropping has a very high EUE because little N fertilizer is used: EUE for US soybean was 840 kg/GJ in 2007 (Keystone Center, 2009)! For wheat, a largely

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[9] Stomatal conductance as usually measured is really leaf conductance (stomatal conductance plus cuticular conductance).

[10] For reference the approx. total energy contents are: petrol (33 MJ/L), diesel (37 MJ/L), electricity (3.6 MJ/kWh), grain of wheat or maize (15 MJ/kg) and soybean (24 MJ/kg).

rainfed crop in USA and Canada, EUE is lower, presumably because of lower yields vs. fixed fuel costs per ha, and has increased less, currently averaging around 300–350 kg/GJ (Fischer et al., 2014).

Another factor contributing to greater EUE has been the switch to reduced and no-till (Pittelkow et al., 2015). The marked decrease in draft energy for tillage is, however, partially offset by the high energy content of the required herbicides (e.g., the energy cost of glyphosate is around 500 MJ/kg a.i) so no-till only decreases input around 10–15%, for usually somewhat better yields. Such results come from long-term experiments with spring wheat in semi-arid Saskatchewan (Zentner et al., 2004) and winter wheat in semi-arid Mediterranean Spain (Hernanz et al., 2014). Targeted weed spraying from "smart" boom sprayers is now reducing the quantities of herbicide used in fallow spraying and perhaps one day will do so for in-crop selective spraying also. Larger energy savings with no-till have been seen with irrigated wheat in India where few extra herbicides are needed. For example, Kumar et al. (2013) found with groundwater irrigated wheat in Uttar Pradesh, India, that conventional tillage had a total energy input of 23.3 GJ/ha while for no-till this was 13% lower, largely because it saved 38 L/ha of diesel or 87% of the land preparation and sowing energy costs. No-till yielded 4.5 t/ha or 10% more, so that EUE was 26% higher than conventional till.

Again China presents a contrast. Across all of China's cropping areas between 1991 and 2012, energy inputs have risen from 25 GJ/ha to reach a huge 47 GJ/ha (Yuan and Peng, 2017a). In contrast to other high-yield cropping regions, however, outputs have risen relatively more slowly, and the energy output-to-input ratio reported by these authors is low and has decreased from 2.0 to 1.4 during that time. The increase in input energy reflects large increases in use of electricity (32% of total input in 2012, mostly for pumping water), fertilizer (28%), and fuel (18%), while manpower has fallen from 25% in 1991–11% in 2012. At the same time the cropping mix has shifted to relatively more low-energy content, high monetary-value crops like fruits and vegetables. Even so, much of the low energy return is obviously due to inefficient machinery and excessive use of fertilizer (nitrogen fertilizer-use efficiency is at or below 30 kg/kgN for all cereal grains. These same authors (Yuan and Peng, 2017b) studied EUE in detail in high yielding supplementary-irrigated rice crops of Hebei Province. The intensive system yielded 9.2 t/ha paddy rice for an energy input of 34 GJ/ha (180 kg N, 4 ML water, 36 person days) while the extensive system, with a higher EUE (333 kg/GJ vs 267 kg/GJ), yielded 8.5 t/ha for an input of 25 GJ/ha (90 kg N, 1.3 ML water, 23 person days). China has obviously intensified its cropping excessively and large improvements in EUE could be achieved by reducing N (and P) fertilizer rates along with better timing and targeting of applications, and through wider adoption of no-till. In India, fertilizer rates are closer to optimum but scope for lifting EUE probably exists there also. In many developing countries, however, and especially in SSA, few external inputs are used and EUE calculations are dominated by the labour component. As these countries intensify cropping, energy inputs per ha will rise but EUE should also increase.

In regions of small yield gaps EUE will ultimately be limited by N fertilizer use (and pumping costs where ground water is used). Energy costs could be decreased by no-till, especially if soil compaction can be avoided by controlled traffic regimes, while biocide energy costs could also be reduced with smarter integrated management of biotic stresses. Precision agriculture is part of both these technologies. The ultimate N cost limit to EUE can be seen for maize in the USA where NUE is unlikely to increase much more than 60 kg maize/kg N fertilizer (Fig. 5) and so restrict EUE to no more than 1000 kg/GJ in N-energy cost alone (using 60 MJ/kg fertilizer N).

Finally, we return to the energy efficiency of biofuel crops, currently amounting to 300 Mt wheat equivalent (Section 2.2) globally, for which performance can be evaluated in terms of energy output/input ratios without the controversy that exists with food crops. If output/input > 1, the process is energetically positive but must be much greater than that to be economically profitable.[11] This level of efficiency can be achieved with some perennial biofuel crops under humid, tropical humid conditions, for example output/input ratios > 5 for C4 crops (e.g. sugarcane) and C3 crops (e.g. oil palm). Legitimate concerns remain, however, because biofuel crops compete with food crops for land, water and nutrients and also, especially in the case of oil palm, with preservation of land currently outside of agriculture for its other values. For these reasons and because of the gradual improvement in cellulose-to-ethanol processes, the conversion of food from crops to biofuel may now be reaching its peak.

A conclusion on all use efficiencies is that they are maximized with modern cultivars and management, provided inputs do not exceed the level needed for close to maximum yield, something that is a risk in subsidized agricultural systems, or with high-value products like fruit and vegetables (Jobbágy and Sala, 2014). Application of Leibscher's Law implies increases or little loss of input efficiency as inputs increase up to the economic optimum, as in many examples presented above. In all cases, however, cropping in low yield-gap regions is probably approaching upper biophysical limits for use efficiency of all resources. And finally, managing inputs to no more than economically optimum levels (at world prices) not only maximises use efficiency but also limits wasteful losses of resources from the system, an issue for the next section.

## 6. Sustainability of intensification

Here we will discuss aspects of our biophysical definition of sustainability, namely as the long-term maintenance, or improvement if feasible to optimize productivity, of the agricultural resource base (water supply, soil, agricultural biodiversity), while protecting the environment. Some prefer to expand the understanding of SI sustainability to include desirable outcomes in the realm of environmental services (e.g., Wezel et al., 2015) and in socioeconomics (Struik et al., 2014), with inevitable political economic (resilience, equity) and normative (moral) considerations. These issues are important (Section 8), but discussion here focuses on our biophysical definition of SI and does not embrace environmental services, in particular because of the subjectivity of their valuation. Climate change can also be considered a sustainability issue because cropping has effects on greenhouse gas (GHG) emissions, and these are discussed later. Also climate trends and change may affect yields, but slowly and adaptation offers many opportunities for well-resourced smart farmers and field researchers to benefit from the positive and counter the negative effects that might arise in our medium-term 20-year perspective.

Water is relevant to sustainability because of the over use of this clearly finite resource, and/or of its misuse that has caused salinization in many irrigated systems. Constraining water use to match annual renewals relates partly to improving WUE already mentioned. It suffices to add here that over pumping of aquifers threatens the sustainability of several major irrigation systems (e.g., the Ogallala aquifer in the western Great Plains of USA, the North China Plain and the north-western Indo-Gangetic Plain), as does over allocation of river water and competition from other users in many places. Salt accumulation in irrigated systems imposes a related sustainability challenge because extra irrigation water must be applied from time to time to leach salt from the crop root zone out of the system, with the added design requirement for adequate drainage. Without this, irrigation systems, especially those lacking regular heavy seasonal rains to leach salt away, are on a collision course with irreversible salinization, as occurred in the Mesopotamian disaster (2300 BCE). On this matter, we express concern

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[11] Bob Loomis was famous for challenging Nobel Prize winning photosynthesis chemist Melvin Calvin and others. They had claimed in the usual prestigious journals that the 1970s energy crisis could be alleviated with biofuel (oil) production from a latex-forming *Euphorbia* species to be grown in the world's drylands. Loomis (1985) pointed out that the calculations of the *Euphorbia* advocates defied the simple physics of crop growth!

over the status of current irrigation systems given that estimates are poor but around 15 y ago, at least 20% of all irrigated lands were considered salt affected (FAO and ITPS, 2015). Engineering solutions are required to ensure success in prevention and/or rehabilitation of salinized areas. Safe removal of salt is, however, not a feature of many of the world's major irrigated schemes in arid and semi-arid regions, which are creeping gradually to failure.

Economists have used trends in agricultural total factor productivity (TFP) as an indirect aggregated index of change in the sustainability of agricultural resources. TFP appears to be increasing at an undiminishing rate, at least up to around 2010 (examples are summarized in Fuglie, 2012; Fischer et al., 2014). But TFP change is difficult to interpret in the present context, and agronomists prefer to work with the natural resource base itself, and in particular the soil. Maintaining soil productivity is the key issue in sustainability, now often referred to as maintaining "soil health". The parameter set of this new term is usually poorly defined, subject to uncertainty, and includes emotive concepts that are of little value (Sojka et al., 2003). For agronomists (and economists) the soil quality to be sustained is that which maximises long term productive capacity of soil for crops (and pastures) at least cost. Importantly this is not necessarily the native condition of the soil that could, for example, be deficient in essential nutrients for plants or animals, or even excessively rich in N and P. Of main interest are key aspects of the soil, under the headings of chemical fertility, and its physical and biological states that farmers can economically manage (Sojka et al., 2003; FAO and ITPS 2015); the latter reference is a huge compendium on soil properties, only a few of which, those most relevant to cropping, are referred to here.

### *6.1. Soil fertility and chemistry*

Soil fertility for crop nutrition is determined by the interacting systems of soil organic matter with its continuous transformations of C, N, P and S mediated by soil biota and the cation exchange capacity (CEC) of the colloidal phase of soils, including the organic matter, that holds and exchanges nutrients with plant roots. The carbon of this organic matter is commonly expressed as soil organic carbon (SOC).[12] Values of SOC less than say 1% in the top 10 cm, often < 0.5%, for example in much of Sub-Saharan Africa as reported by Craswell and Vlek (2013), lead to severe deficiencies in one or more of the major elements (N, P, K, S) and micronutrients also (Zn, Mo) essential for plant growth. SI aims to supply sufficient nutrients (either as fertilizer, or where available, manure or compost) to remedy this lack, and ultimately to reach a steady state SOC level whereby the application of nutrients balances those lost in crop products delivered at close to potential yields and lost through other routes (e.g. nitrate leaching, gaseous N emissions, P fixation into very poorly available forms). Under this condition SOC will be usually well over 1% and may approach 2.5% (Connor et al., 2011). As far as adequate crop nutrition is concerned it need go no higher. Many forest and especially grassland soils have lost up to half or more of their original SOC in nutrient-mining phases during the first several or many decades of cropping and must now be stabilized at some intermediate SOC for sustainable cropping. In southern Australia SOC of soils under leguminous pastures that were rotated with crops in common ley-farming cycles of 4–8 years usually fluctuated between SOC levels of say 1.8% (end of pasture phase) and 1.4% (end of cropping phase).

These responses to inclusion of legume–based grazed pastures in wheat production systems are depicted in Fig. 6a in terms of topsoil N content that in general is ca. 8% of SOC as humus. Fig. 6a shows the continuing decline in N content to exhaustion levels under a long-term fallow-wheat rotation and how recovery can be achieved with a continuous legume pasture phase and more slowly with, in this case, a sequence of two wheat crops following a four-year pasture phase. This information is then the basis for a generalized management practice that uses legume-based pasture to return N fertility to an upper working level from where two or more successive wheat crops can economically exploit the accumulated fertility down to a working level before a return to pasture to recover fertility for the next cropping phase. This general model has many variants in terms of length and composition of pasture and crop phases depending upon soil and climatic conditions, and is not unlike the strategy adopted in Iowa before the arrival of N fertilizer in the 1940s, as described in Loomis (1984).

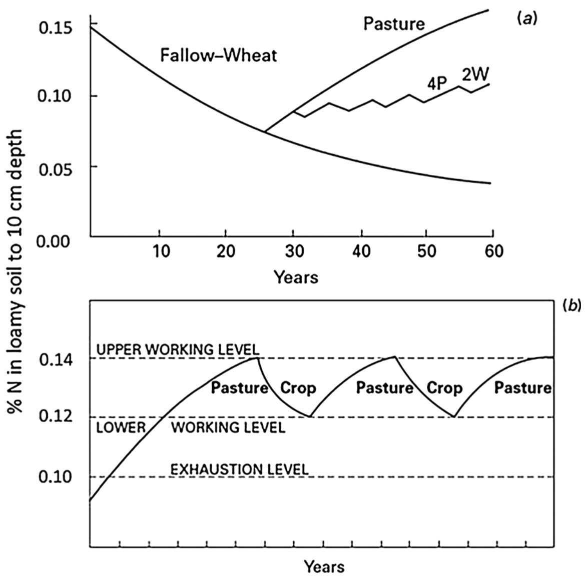

**Fig. 6.** (a) Nitrogen fertility trends in fallow-wheat, legume pasture, and pasture-wheat sequences in southern Australia (4P is four-year pasture and 2W is two-year wheat). (b) Recovery of nitrogen fertility by legume pasture and its maintenance with pasture-wheat sequences.
Adapted from Greenland (1971) and Rovira (1992).

It is not sensible to blame SI for SOC levels below original values, returning to which would sequester large quantities of nutrients (N, P, S and maybe others) at high cost to farmers (Kirkby et al., 2011),[13] and increase the chance of wasteful losses. Some soils, deficient in certain major or minor elements in the native state, actually achieve higher nutrient and SOC levels under SI, as has occurred over significant areas of southern Australia (Smith 2000). Available nutrient levels and SOC continue to be the best indicators of sustained soil fertility, in contrast to the multitude of new microbiological measures that have been studied recently in this context (e.g., de Castro Lopes et al., 2013).

Both insufficient and excessive fertilization cause soil degradation yet fertilization at any level often carries a stigma in the popular media, with accusations of degradation of soil and environment. Excessive fertilization certainly causes environmental degradation, as can be seen today with N and P pollution in China, whereas in other humid environments this occurs to a lesser extent depending on management and the constraints of normal pricing and regulation. Soil acidification is, however, an inevitable response of soils under cropping because, depending on CEC buffering capacity, these soils gradually lose basic cations in harvested produce (especially leguminous products), and because nitrate leaching in fertile soils in humid environments leaves behind $H^+$ cations. Consequently regular liming is essential to keep pH

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[12] Soil organic matter is approximately 1.7 times the soil organic carbon (SOC); both measures exclude the undecomposed residues of plants and animals, although this is often difficult to achieve. SOC is approximately 12 times soil organic N.

[13] SOC is largely in humus that contains relatively fixed proportions of C:N:P:S (100:8:2:1.4). Thus 0.1% SOC in the top 10 cm across 1 ha amounts to 1.3 t of carbon; it would also contain about 104 kg N, 26 kg P and 18 kg S, which if supplied by fertilizer would together cost over USD120 at current prices.

above a lower limit, and has been practiced by farmers for millennia. A lack of nearby supplies of lime or other alkaline materials could one day become a concern for sustainability in some regions. Other chemicals can also threaten soil sustainability. These include natural cadmium contamination in P fertilizers, arsenic from pumped aquifers in arsenic-rich sediments, and heavy metals and organic chemical contaminants in animal manure, urban sewage and compost. Regular monitoring of these sources is essential but proper use of synthetic fertilizers ensures rather than threatens sustainability.

The prohibition of synthetic chemical fertilizers, at least for supply of N and P, is a major limitation to the productivity of organic farming. While there is a market for high value niche products of organic farming there is simply not enough manure to supply more than a tiny fraction of the N and P needed by the world's crops, even if it could be delivered to where it is needed. Centuries of experience with legume farming before the expansion in use of synthetic N from the mid 1900s established that periods of legume-based pasture could support subsequent non-legume crops as discussed previously with respect to Fig. 6. Possible values of soil N accumulation under legume crops or pasture range from 100 to 300 kgN/ha/y (Peoples et al., 2009) but crops are not effective unless they are incorporated in the soil before seed set because harvesting removes most, if not all, the fixed N benefit, as mentioned early for soybean (Salvagiotti et al., 2008). In the 1950s, Australian wheat farmers typically grew leguminous pasture on 50% of arable land with corresponding smaller wheat production compared with what has now become possible by cropping with fertilizer N and new yield responsive cultivars. These higher yields in modern cropping further disadvantage the relative productivity of present-day organic systems.

Proposals to feed the world more sustainably with organic farming appear from time to time in prestigious journals (Badgely et al., 2007; Seufert et al., 2012; Ponisio et al., 2014) including some very detailed recent modelling (Muller et al., 2017). However the analyses fail at the first step because they assume that organic manures are freely available, as they are in some parts of Europe, and do not address the issue of the cropping land that must be allocated to legume crops to support the entire cropping system (Connor, 2013; Stewart et al., 2013). All cases inevitably never refer to sourcing the N to replace the more than 100 M tons of synthetic N fertilizer currently used annually in world agriculture (at a fixation rate of 100 kg N/ha/y it would need over 1000 Mha of legumes, or more than two thirds of all arable land). In the face of this dilemma, the organic farming proponents (e.g. Muller et al., 2017) resort to constraining food demands (e.g., restricting meat consumption, eliminating waste) to close the nutrient cycle, a totally different issue.

The use of biocides (herbicides and pesticides) generally increases with intensification, although there are many exceptions (e.g. insecticide use has declined markedly where Bt transgenes have been deployed); also use can be greatly tempered by integrated management systems. Many biocides, being charged molecules, are absorbed onto the clay and inactivated upon reaching the soil, but some appear to breakdown only slowly (e.g. triazine herbicides, or aminomethylphosphonic acid (AMPA) derived from glyphosate), and may cause damage if the following crops are susceptible (Duke et al., 2012). There are many claims but no evidence, however, that soil sustainability is threatened, but biocide use does require skilful management and ongoing monitoring.

### 6.2. Soil physics

The physical status of soil relates to water infiltration and water storage capacity, and to soil structure for good aeration and easy root growth; all are generally positively related to SOC. High infiltration (which avoids ponding and runoff) depends on high hydraulic conductivity between the surface and deeper layers, and is most damaged by surface sealing in heavy rain (or sprinkler) events. Tillage and macro-faunal activity create the continuous pores that soil surfaces need for fast infiltration, but only surface cover by crops and their residue can prevent surface sealing due to rain drop action, delivering generally spectacular positive effects on infiltration rates. The widely acknowledged advantage of no-till that retains crop residue on the soil surface and encourages macro-faunal activity, derives from reduced soil evaporation and especially increased infiltration, with associated advantages of reduced runoff and erosion. Soil water storage capacity, especially important in rainfed cropping, increases with SOC but benefits are often exaggerated. Thus increasing SOC from 1% to 2% in the top 10 cm, a large increase, would increase available water storage between 4 and 6 mm depending on texture (Hudson, 1994), but the extra water in the topsoil could be more subject to evaporative loss. SOC is more important physically for the earlier mentioned reasons.

Cultivation associated with cropping has with few exceptions (e.g. paddy rice agro-ecologies of Asia) been the cause of huge topsoil loss by water and wind erosion; soils have thus become degraded, irreversibly so in extreme situations where land deformation through gully formation is marked and/or soils are shallow. It was not until the advent of herbicides that permitted no-till and crop residue retention on the soil surface, that modern agriculture had a fairly satisfactory answer, reducing erosion rates by over 90% through greater infiltration, reduced soil detachment for transport, and reduced overland amounts and flow velocities (e.g., Freebairn et al., 1993). The global conservation agriculture (CA) movement has built on the two principles of reduced soil disturbance and soil cover by adding a third one (crop rotation), but even with their enthusiasm and the clear advantages, no-till is only being adopted slowly, even in the rainfed crop lands of Sub Saharan Africa, Asia and the Mediterranean where it is most beneficial. There are serious barriers to adoption in small holder systems, particularly in Africa and the Middle East arising from many factors including the complexity of the CA technology package, and competition for crop residues traditionally used as animal feed (e.g., Giller et al., 2015). In some places, however, with appropriate circumstances, small holders have adopted the practice, as first seen in Paraguay and parts of southern Brazil, where there is > 90% adoption, and more recently in over 2 Mha in the irrigated wheat lands of northern South Asia (Hobbs et al., 2017). In South America control of water erosion initially drove the no-till revolution, whereas in the irrigated Indo Gangetic Plains other advantages predominate (e.g. earlier wheat seeding, fuel saving). As with all new technologies, but especially given the huge break with tradition that no-till represents, systems must be adapted and demonstrated under farmers' circumstances; machinery and institutions must be appropriate, and management will become more complicated, but this is the inevitable nature and challenge of SI.

### 6.3. Soil biology

Soil biology is often mentioned in the context of "soil health" and sustainability. Despite the large recent expansion of research in this area, with the new molecular tools for microbe identification, and the obvious role of microorganisms in nutrient cycling (and losses like $N_2$ and $N_2O$ emissions), its importance for crop productivity remains unclear (most plants grow perfectly well in hydroponics). Biotic stress agents are recognized but even their ability to thrive and cause damage is poorly understood apart from empirical observations of the benefits of rotation with certain non-host and allelopathic crops, and of the mysterious decline of some pathogens with continuous culture of the host crop. Microbiological additives, commonly as seed dressings, are promoted but apart from mycorrhiza in some circumstances and *Rhizobium* more generally, have no reliable effects on productivity. Prospecting for, and selection of, elite strains of *Rhizobia* specific for crops and sites has been long practiced elsewhere and is now being newly applied to improve provision of BNF to increase crop productivity in Africa (Woomer et al., 2014). Success in the field requires commercial production of the appropriate inoculum for distribution to farmers but appropriate fertilizers also. P is generally deficient but other nutrients (K, Mg, Zn, Mo) are often also required.

In conclusion, there is as yet no clear scientifically proven link between microbial diversity and soil function or crop productivity (Kuyper and Giller, 2011). Macro-faunal activity (e.g. earthworms) has, however, always been recognized as a valuable component, for incorporation of aboveground biomass in the soil, as also for construction of continuous biopores with the soil surface, and is promoted by no-till.

### 6.4. Biodiversity in cropping

Cropping biodiversity refers to the crops themselves, to beneficial organisms such as pollinizers and soil microbes, and to noxious organisms, in particular weeds, pests and diseases. This is a vast subject so that only some key issues relevant to sustainability can be raised here, as well as leaving aside non-agricultural biodiversity in cropped landscapes, the question of sparing or sharing. Greater attention to these subjects can be found in Nösberger et al. (2001), Lenné and Wood (2011) and Fischer et al. (2014).

The potential genetic diversity of our crops is large and much is now reasonably well preserved *in situ* and *ex situ*. The challenge is to utilize it in modern plant breeding, a task now for private as well as public pre-breeders. Many of our crops are already protected against diseases and pests as a result of past efforts to diversify host plant resistance. There have been no major epidemics in modern cropping since the southern corn-leaf blight epidemic in USA in 1970 that destroyed about 20 Mt or 15% of national maize production (Bruns, 2017). Monoculture, in which all plants in the field of a crop are similar genetically, remains a hallmark of modern cropping, but the phenotypic uniformity of cropped landscapes, so alarming to the non-agricultural observer, belies the underlying between-cultivar (spatial) and within-cultivar (genetic) diversity in the host-plant resistance genes deployed. Even so, the ongoing effort of pathologists and breeders to replace host-plant resistance genes as they become ineffective with the emergence of new biotypes of pathogens, known as maintenance breeding, absorbs large resources but it must continue as also must the search for more durable natural resistance genes. The use of resistance genes arising from genetic engineering (GE) has been hugely successful, for example, in cotton, corn and soybean, giving more durable resistance to major insect pests and substantially reducing biocide use, and such examples are likely to become more common, such as the recent approval of late-blight resistance in potato, created by using GE to stack multiple natural resistance genes. Host-plant resistance breeding requires considerable resources for continuing effectiveness, as argued by Tabashnik and Carrière (2017) in a recent review of Bt insect resistance. If more durable GE solutions to pests and disease can be found, this would free up breeding resources for concentration on other targets including PY. There are good prospects that host- plant resistance breeding in all its forms, and now combined with integrated pest and disease management, will very likely ensure even more sustainable crop defence in the future, with less risks to human health and the environment from biocide use.

Weeds are another continuing threat to sustainability in cropping. They limit the crop area that small holders can manage with hand hoes and animal-drawn tools, and cultivation for weed control causes soil damage. While herbicides have played a huge role in weed management, including non-GE and now GE herbicide-resistant crops, it will likely never be possible to rely solely on herbicides. Weeds will continually evolve to challenge most if not all management strategies. Complex integrated weed management (IWM) is essential and offers a sustainable solution. Australian wheat farmers, for example, use multiple IWM tools besides single herbicides, including herbicide mixes and their rotation, spraying to target only weed plants, competitive cultivars and row spacing, weed-seed destruction at harvest, weed-seed collection and disposal, windrow and stubble burning, strategic cultivation, green and brown manure or cover crops, pasture phases and grazing in general,[14] and smart crop sequencing.

Crop sequences and rotations, that deploy crop diversity in time, can bring other sustainability advantages besides easier weed control. These include reduced levels of soil pathogens by including non-host crops, potential for net gain of soil N by legume crops, residue from cereals to protect the soil after crops with poor residue persistence such as pulses, and sometimes poorly-understood beneficial soil microbial changes (e.g., Angus et al., 2015). Currently the world has much continuous monoculture, especially of cereal crops in the developing world, yet some sequences, such as continuous rice or rice-wheat double cropping, are remarkably sustainable, possibly because of alternating periods of soil saturation and non-saturation. Other binary rotations are also widespread, including maize-soybean (e.g. USA, Brazil, Argentina), wheat-cotton (Pakistan), wheat-maize (China, Pakistan), and wheat-soybean (Argentina) and seem quite sustainable. At the same time, more complex rotations including more beneficial broad leaf crops such as pulses, oilseeds, new crops, and green manures, are poorly represented. This often reflects a lack of research on the less important crops not the mention any potential new crops, and less well developed markets (or lack of price subsidy) for them.

Traditionally in parts of Europe and the New World, inevitably with adequate security for unattended animals, fields were fenced and cropping was rotated with periods of grazed leguminous pasture (ley farming), bringing the soil benefits mentioned earlier and diversifying sources of income. Loomis and Connor (1992) devote a chapter to this farming system. Shepherded daytime grazing of crop residues and/or their feeding, along with cut forage, to stall-fed animals with return of some manure, so common in the developing world and dictated by tradition and security, is a poor substitute for ley farming. But with simplification and specialization of cropping, ley farming (and fences) have disappeared from many modern cropping landscapes, largely remaining now only in parts of southern Australia and South America. System diversification with grazing animals, where climate and markets permit, is likely more sustainable than 100% cropping. It can stabilize income, facilitate nutrient recycling, and offer more opportunities for management of crop residue and integrated weed and pest control. Australian wheat farmers are grappling with the challenge of bringing animals and legume pastures back into the system as livestock/grain price ratios and herbicide resistant weeds steadily move to favour this option. EMBRAPA in Brazil proposes to integrate pastures (*Brachiaria* and *Stylosanthes* spps) for cattle grazing into the now common no-till maize-soybean system in the cerrado. Both solar-powered electric and virtual fencing should facilitate the move back to animal-crop integration. In virtual fencing, animals are tagged electronically and guided to remain within defined geometric boundaries without fences.

Cropping diversity at a spatial scale is a final issue worth mentioning. It is especially evident in traditional cropping and is now a strong feature of the agricultural landscapes of Western Europe. The common diverse mosaic of naturally occurring climax plant communities, where it can still be seen, reminds us of the underlying diversity in slope, aspect, and soil type and depth (Passioura, 1999). Small scale cropping can take advantage of this, as well as bringing certain environmental services (Nösberger et al., 2001). With large scale cropping (large machines and large fields) that now dominates in the New World and Russia Plus, underlying environmental variation used to be a challenge for setting appropriate input rates. Even this issue, manageable in traditional farming and where fields are small relative to the original natural variation, is yielding to the tools of precision agriculture and variable-rate applicators for inputs. Again sustainability is advantaged, but the growing scale of cropping brings some questions regarding machinery weight and soil compaction,[15] the loss of some environmental services such as barriers to the accumulation and overland flow of excess water, and other questions for today's society that can only be flagged here. The latter includes the relentless substitution

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[14] The use of sheep, specially trained to eat only weeds in crops, is being studied. Their use to clean up grain left on the ground after harvest and thereby reduce the build up of mouse populations is also noted.

[15] Field operations using smaller autonomous vehicles, perhaps operated in swarms, may spell the end of scale advantages through ever larger machines.

of capital for labour in the name of cheaper food, and the minimization of land sharing with beneficial non-agricultural nature, for example in field boundary vegetation.

### 6.5. *Protecting the environment: off-site environmental impacts of cropping*

Only negative off-site impacts are mentioned here and some of these have been introduced previously, e.g., N and P movement into waterways, rising saline water tables, and water and sediment arising from soil erosion. Obviously the movement of N and P in water are most serious in humid, low evapotranspiration environments of Western Europe, eastern China, and Eastern/Central USA. Generally off-site pollution is minimized with proper use of inputs as already discussed, a win-win pathway for farmers, but to date only Western Europe seems to be making progress on this front. For example Iowa was highlighted earlier for its gains in crop productivity, but N management is still well short of best practice and undoubtedly this has driven ongoing nitrate pollution of its rivers (e.g., Hatfield et al., 2009).

A related area warranting attention is the emission of greenhouse gases (GHGs) in cropping (about 8% of all global emissions according to IPCC (2007)), dominated in particular by $N_2O$ (about 50%), as part of the nitrification-denitrification cycle in wet fertile soils, methane (about 20%) from paddy rice culture, while the rest is $CO_2$ from fossil energy involved in activities already described, but especially coming from manufacture of N fertilizer (Connor et al., 2011). As with use efficiencies, the key issue for GHG emissions is the yield-scaled value (kg $CO_2$ equivalent per kg grain). The estimates for $N_2O$ are especially uncertain, being based on 1% of the N in the fertilizer N applied; the number is likely higher in humid environments, especially anaerobic soil situations, and much less in drier ones. Technologies to improve NUE at the crop level (Section 4.1) by supplying N to match crop demand are also those that will lessen $N_2O$ emissions (e.g. van Groenigen et al., 2010). All these areas will benefit from much more research. For example, the anaerobic soil conditions of traditional irrigated rice favours methane production, averaging 134 kg/ha (3.1 t/ha $CO_2$-equivalent, Linquist et al., 2011), leading to an average greenhouse warming intensity of 0.66 kg $CO_e$ ($CH_4 + N_2O$)/kg grain, approximately four times that of wheat and maize crops (Fischer et al., 2014). However it is recently reported that rice culture under an alternate wetting-and-drying regime can substantially reduce methane emission while not causing increased $N_20$ losses (Chu et al., 2015; LaHue et al., 2016), results confirmed in detailed measurements of $CH_4 + N_2O$ emissions in no-till rice-wheat in northern India (Sapkota et al., 2017). And Su et al. (2015) claim to have GE paddy rice with almost zero methane emission.

Finally an area of some controversy in the GHG debate is the widespread promotion of sequestration of soil organic carbon (SOC) as a sink for atmospheric $CO_2$. It has, for example, been calculated that raising SOC by 4 parts per 1000 (of SOC) per year in the top 1 m (about 0.6 t C/ha/y) across all agricultural lands would sequester around 20–35% of annual global C emissions (Minasny et al., 2017). While this would also be desirable for the world's depleted soils for other reasons, and could probably be done with extra nutrients (e.g. Kirkby et al., 2016), the large opportunity cost in N, P and S sequestered in the extra humus, as discussed earlier, would be very difficult to justify once soils have reached a satisfactory level for sustainable cropping. Sequestering C as biochar (likely to contain much less N, P and S) has also been proposed but many obstacles must be overcome for this to be feasible at scale. The major impact of cropping on net $CO_2$ exchange with the soil lies in yield increase preventing further clearing of grassland, woodland and forest for cropping (Burney et al., 2010). Tilman et al. (2011) calculated that clearing and cultivating releases about 30 (grassland) to 150 (forest) t C/ha as $CO_2$ in the process. Far less GHG would be produced if extra N fertilizer were manufactured and applied to existing infertile croplands to boost production by an equal amount of grain delivered by land clearing. This argument for land sparing by yield increasing technologies has been, however, challenged by the expansion of cropping into the Brazilian cerrado (e.g., Angelson and Kaimowitz, 2001). This could be true regionally, but a global view may show no net GHG effect, because the resultant lower grain prices arising from cropping expansion on favourable new lands will have encouraged the reforestation of more marginal croplands (e.g. in eastern USA, China and Europe).

## 7. Farm management: a key element for sustainable intensification

Dealing with all issues of natural resource-use efficiency and sustainability is obviously complex. Taking a 50% yield gap down to 25 or 30%, at the same time as PY is increasing, is a slow process (e.g. Iowa maize, USA soybean, UK wheat, in Fischer et al., 2014) and also managerially complex. Neither are "transformational", both are decidedly incremental and involve the refinement of many technologies, some yet to be discovered, and are ultimately dependent on the technical and managerial skills of farmers and their advisers.

Skilled management began with indigenous knowledge of subsistence farmers, where its development was constrained by the limited options then available, being restricted to slash and burn or to scrounging the countryside for nutrients and keeping and planting the best seeds, often wisely intercropped. Under those circumstances, the annual cycle of farming was dominated by overwhelming, mostly human, physical input required to cultivate and sow at the right time, control weeds however possible, and finally to secure the meagre harvest at maturity. Development of attitudes to sustainable management was, and remains in many places emerging from these conditions, constrained also by lack of secure land tenure.

It is a large jump forward to a modern tenured family farm, passing over distinct intermediate phases, for example traditional farming of the early to mid 20th century in USA, where education and literacy were first seen as key elements in change (Loomis, 1984). In today's modern farm the owner/manager is likely full time managing cropping decisions, sourcing credit, purchasing inputs and forward selling products; selecting crops and cultivars, planning sowing dates according to field history and past and present weather and market forecasts; choosing fertilizer rates linked to history, spatially-determined fertility indicators and the weather; planning strategic and tactical use of biocides within complex integrated management packages; arranging deployment and maintenance of multiple machines; keeping appropriate financial, field and accountability records; and reporting to comply with a host of regulations. Adding pastures and grazing animals into such a cropping enterprise probably more than doubles decision-making and the requirement for skills. And across the whole span of cropping is the need to keep up with and trial new technologies, which are arising all the time. Thus modern farmers now usually have outside technical support, ranging from public sector agents, input suppliers, to hired private agronomists, increasingly delivered on site through wireless internet. Variation in decision-making skill contributes strongly to the variation in field and farm productivity found within any given natural resource domain. But there are also differing family goals, including variable aversion to risk and the element of chance, because the best management strategy remains uncertain in the face of inadequate knowledge, especially about the immediate future. We would claim, however, that any well-informed farmer with secure land ownership has as another goal, namely its sustainability, as defined here, although realizing this goal can be threatened when profits are marginal.

There was a time when commercial family farmers knew more about the possibilities and limitations of their farm than anyone else and were more committed to the work required than hired workers, whose number rarely exceeded one per farm. The family farm is still dominant in cropping across the world (Lowder et al., 2016) because of such comparative advantages. But now, with increased scale and complexity of modern farming, these advantages may be insufficient, promoting an increase in corporate farming as a means to bring more specialized knowledge and financial tools to the many crucial management and marketing decisions. It is not clear whether family farmers working together with advisers, and in family partnerships, co-operatives, district farmer groups and other knowledge-generating and sharing partnerships, can compete with the steady corporatization of farming. But either way, the efficient production of goods and the sustainable management of resources should ensue, aided by fair reward for resource maintenance in the latter case, and by better agricultural science knowledge and secure land tenure.

## 8. Alternative visions, contested agronomy, and wicked trade-offs

Needless-to-say there is concern arising from perceived problems with sustainable intensification, including among agricultural scientists. Environmental concern intensified in the 1960s with the publication of Silent Spring (Carson, 1962), the excesses of the Common Agricultural Policy of the EU (de Wit, 1988), and overuse of pesticides in some rice systems following the Green Revolution in Asia. Equity issues that were raised regarding the Green Revolution were clearly outweighed by the gains (e.g., Paarlberg, 2013). Notwithstanding progress combating food insecurity and managing excess use of inputs in modern cropping, the concern and even opposition continues today. These views can be seen in documents such as the International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD), see McIntyre et al. (2009), a supposedly international consensus of the way forward for agriculture supported by the World Bank and the United Nations, but rejected by USA, Canada and Australia and others for its many flaws (e.g., Wood and Lenné, 2011). They can also be seen in disagreement about appropriate agronomic interventions in the developing world (contested agronomy, as outlined in Sumberg et al. (2013) and advanced in a 2016 conference entitled “Contested agronomy: whose agronomy counts” (https://contestedagronomy2016.com), and more general disagreement regarding the way forward in global agriculture (the socioeconomic and normative issues surrounding intensification (e.g., Struik et al., 2014; German et al., 2017)). An excellent up-to-date view of this confusing situation is provided by Giller et al. (2017) who optimistically foresee a possible golden age for agronomy.

Space does not permit a detailed discussion of all these areas of disagreement. Disputation in agronomy includes the role of organic farming free of “synthetic” chemicals, the place of conservation agriculture in SSA, the System for Rice Intensification (SRI), the use of F1 hybrids and genetically engineered traits, energy use in agriculture, diversification in production systems, cropping sequences and polyculture *v.* monoculture, etc. Some seek a much more diverse agriculture (e.g., IPES-Food, 2016) while others cannot foresee a developing agriculture with purchased inputs. Many argue for farming according to ecological principles, the “agroecology” movement, while failing to recognize that this is already the basis of agriculture, enshrined in the title and contents of Loomis’s book, *Crop Ecology*, in de Wit’s old Department of Theoretical Production Ecology, and the writings about ley farming, for example in Australia (Smith, 2000). In most cases, however, the solution lies not in semantics but in a willingness to understand the farmers’ needs, aspirations, skills and resource limitations, on which Loomis would have advocated engagement in relevant scientifically-sound experimental exploration of options and careful measurement of inputs and outputs. The example presented at the outset as Fig. 2 is such an exploration, in that case of the stepwise adoption of reliable innovations: small doses of N and P fertilizer, use of modern cultivars, and weed control by herbicide to retain ground cover. But those agronomic innovations are just the entry into a much larger social and economic dimension. Farmers can make the adoptions only if the required inputs are available and affordable relative to prices they can obtain for the sale of extra production. Formation of strong farmer groups and the engagement of local agribusiness also strengthens the chance of successful intensification of cropping systems.

At a broader level of concern are views that emphasize the many trade-offs that SI brings. These can be in the areas of adverse environmental and biodiversity impacts and undesirable social outcomes (e.g. Struik et al., 2014; German et al., 2017), including issues of equity, human welfare and nutrition, excessive scale and specialization in farming, and consequences for viability of rural communities. As Struik et al. (2014) point out these are normative issues, susceptible to moral judgement, and as such create for society what can be called “wicked” problems of balancing wins and losses, although win-win outcomes are also possible (German et al., 2017). Resolution where there is such conflict must depend on a hierarchy of priorities that could be in rank order:

1. for all at all times, abundant, affordable, healthy and nutritious food
2. for farmers, comfortable stable incomes, in line with the rest of society, from sustainable farming with less drudgery
3. for the non-farm environment, absence of encroachment and of contamination by farming
4. for the rural communities, viable support and attractive farm landscapes, and
5. for the world, maintenance of non-agricultural biodiversity.

This could at least be the priority order for the developing world, but one gets the impression some in the North would rearrange these priorities, and much of the contestation seems to have its roots in this. SI, as defined earlier, targets (1) and (3), and almost anything that threatens crop-yield increase jeopardizes farm sustainability and these goals directly (1) or indirectly (3 and 5). It leaves the second goal to market forces and national policies. The fourth and fifth goals are also questions of culture and policy: land sharing and diversity is weighted heavily in Western Europe, but it is land-sparing yield increases that on a global scale will likely best protect biodiversity in as yet uncleared arable lands. The immediate trade-offs that loom large for agricultural science are those within the first and third goals above, namely the need to free crops from biotic stresses and to manage crop root zones at high nutrient levels for greatest productivity. This brings greater risk from natural selection pressure against all biotic-stress control strategies, and from $NO_3$ leaching and $N_2O$ emissions, all especially evident in humid environments. As has been discussed earlier, many of these negatives could well yield to new technologies, making increased research in these areas an imperative. But some are more intractable: e.g. increased scale in cropping for economic (labour) efficiency gains seems essential if per capita farmer income is to rise as elsewhere in any modern urban-dominated economy, as Loomis pointed out some time ago (Loomis, 1984), yet this has inevitable implications for rural communities. To propose to reverse this process of increasing scale, that currently maintains farmers as < 5% of the workforce in developed countries, and replace it with more labour-intensive diverse small farms (e.g., IPES-Food 2016) is reversing more than 100 years of economic development and is simply unrealistic. Urban consumers need to make informed rather than emotional and dogmatic decisions on food purchases and to better understand the intentions and challenges of environmental care in modern agriculture. They must be ready to pay a great deal more for food if greater constraints are placed on food production in the interests of the environment.

## 9. Conclusions

- This paper honours Professor Bob Loomis, a colleague and leading agricultural scientist. We look at the challenges for agricultural science in the short-to-medium term as cropping sustainably intensifies across all the world’s arable lands to meet continuing growth in demand for crop products, and in poorer nations, to alleviate rural poverty and drive economic growth.

- Two major regions (Sub-Saharan Africa and West Asia-North Africa) show very large gaps between farm yield and potential yield (> 100% of farm yield, often > 200%). Closing these yield gaps demands immediate local adaptive research and will inevitably involve the adoption of the same sequence of largely agronomic technologies that has occurred elsewhere over the last century. However, many other barriers, often off farm and involving institutions, infrastructure and policies, must also be attended to so that this progression is accelerated immediately, lifting farm yield growth to 2% p.a. or more.
- The remainder of the world has substantially intensified its cropping as reflected in smaller yield gaps (< 100%) such that farm yield progress depends much more on skilled juggling of existing technologies and on the advancement of potential yield through breeding and agronomy, and their positive interactions, as we have seen over the last century. Current PY progress is between 0.5 and 1.0% p.a. across most crops, and exploration of prospects in these areas concludes that greater progress in the medium term (20 years), when it is most needed, is unlikely. Farm yield should continue to progress sufficiently (1–1.5% p.a.) to meet growing demand in all these regions as remaining yield gaps shrink further, and allow the New World and Russia Plus to supply the growing exports required by WANA and SSA, and anywhere else.
- Efficient use of natural resources in cropping (nutrients, water, energy) is another goal of agricultural science and is not threatened by sustainable intensification provided inputs are managed skilfully so as not to exceed crop demand. However, there are strong biological limits to the use efficiency of most inputs, and these are being approached by the best farmers.
- Sustainability has a biophysical component that relates to maintaining soil productivity and agricultural biodiversity forever, and protecting the non-agricultural environment. Intensification of inputs is essential for adequate soil fertility (chemical, physical and microbiological). Where SOC is less than 0.5% it must be restored to higher levels, however difficult, but building levels beyond that needed to maximize crop productivity, with removed nutrients being regularly replaced, is unnecessary and expensive for farmers in terms of nutrients sequestered with the carbon.
- The sustainability of cropping is most threatened by the evolution of biotic agents (weeds, pests and diseases) and this will require sophisticated integrated management, embracing all the available tools, including genetic engineering.
- Sustainability is also challenged by chemicals escaping croplands, principally nitrate by leaching and nitrous oxide and methane by emissions. Much more research is demanded and should deliver solutions without sacrificing crop yield. The land sparing impact of farm yield increase remains ultimately the greatest contribution of agricultural science to the environment.
- The skilful management of cropping needs to be highlighted as an overlooked critical aspect of efficient resource use and sustainable intensification. Everywhere this must involve education and training for farmers, farmer groups, public and private farm advisers, and researchers, aided by the tools of modern information analysis and communication.
- Recently many aspects of sustainable intensification are more openly contested amongst agronomists, scientists and the public. The answers often require recognition that low-input cropping cannot feed the world or protect the environment, and more applied and often local agronomic field research with careful measurement of inputs and outputs under farmer circumstances is needed in the developing world.
- In a broader sense, however, some contestation involves normative goals and societal priorities. These will vary between cultures and depend on the stage of agricultural development, but seem likely to increase through inexorable worldwide urbanization. Contestation is largely driven by poorly-informed views amongst affluent well-fed urban societies and creates unhelpful confusion in developing regions.

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