Crop intensification, land use, and on-farm energy-use efficiency during the worldwide spread of the green revolution

Pedro Pellegrini[a,1] and Roberto J. Fernández[a]

[a]IFEVA, Facultad de Agronomía, Universidad de Buenos Aires, CONICET, Buenos Aires C1417DSE, Argentina

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We analyzed crop production, physical inputs, and land use at the country level to assess technological changes behind the threefold increase in global crop production from 1961 to 2014. We translated machinery, fuel, and fertilizer to embedded energy units that, when summed up, provided a measure of agricultural intensification (human subsidy per hectare) for crops in the 58 countries responsible for 95% of global production. Worldwide, there was a 137% increase in input use per hectare, reaching 13 EJ, or 2.6% of the world's primary energy supply, versus only a 10% increase in land use. Intensification was marked in Asia and Latin America, where input-use levels reached those that North America and Europe had in the earlier years of the period; the increase was more accentuated, irrespective of continent, for the 12 countries with mostly irrigated production. Half of the countries (28/58), mainly developed ones, had an average subsidy >5 GJ/ha/y (with fertilizers accounting for 27% in 1961 and 45% in 2014), with most of them (23/28) using about the same area or less than in 1961 (net land sparing of 31 Mha). Most of the remaining countries (24/30 with inputs <5 GJ/ha/y), mainly developing ones, increased their cropped area (net land extensification of 135 Mha). Overall, energy-use efficiency (crop output/inputs) followed a U-shaped trajectory starting at about 3 and finishing close to 4. The prospects of a more sustainable intensification are discussed, and the inadequacy of the land-sparing model expectation of protecting wilderness via intensified agriculture is highlighted.

EROI | Jevons paradox | land sharing | land sparing | water–energy–food security nexus

The type of agricultural technology developed after the Second World War, known as the "green revolution," came under early environmental criticism (1). Besides reliance on harmful first-generation pesticides and soil deterioration caused by excessive fertilization and compaction and erosion linked to the use of heavy machinery, it was clear from the onset that the technologies required to realize the genetic potential of new crop varieties and hybrids also had a strong dependence on fossil fuels. *Eating Oil* (2) was the revealing title of a book published after the energy crisis of the 1970s (around the time of the US oil production peak). By then, the work of pioneers such as Odum (3) and Pimentel et al. (4) had already highlighted that this form of agriculture was unsustainable and was able to attain high yields only thanks to the energy subsidies represented by equipment, fuel, chemicals, and other supplies. They suggested a straightforward way of assessing the energy-use efficiency (EUE) of production systems: their output–input ratio, i.e., the relation between the solar energy fixed by crops (as chemical energy in grains and other usable products) and the input energy embedded in all human supplies, leaving sunlight aside. This metric is equivalent to the first type of energy return on investment (EROI) of Pelletier et al. (5): the energy return in human-edible food or usable product on the industrially mediated energy investment.

Early analyses showed that EUE decreased as intensification (supplies used per unit area and time) increased, as expected by the economic diminishing-return theory (6). Most of the later work that we are aware of has focused on a particular country, product, and/or production technology, such as conventional vs. organic (e.g., refs. 7–12), and although some performed international comparisons (13–15), apparently none has searched for long-term, global trends. Otherwise, it is difficult to understand why, even when some analyses point to an increase in EUE (e.g., refs. 11 and 15–18), there are authors that keep citing early work such as Pimentel et al. (4) as the basis for claiming unavoidable larger increases in supplies' use than in production. Reviews by Woods et al. (19) and Pelletier et al. (5) covered the entire food system and highlighted a paucity of data for developing countries. Our goal was to address these gaps for crops. An analysis of livestock production was out of our reach, because it would have entailed tracking the (direct and indirect) use of plant products for fodder within as well as between countries.

Taking advantage of FAOSTAT, the global database that the United Nations Food and Agricultural Organization started in 1961 (20), complemented by the best available energy conversion factors [ECs; energy required (MJ/mass) for the production process of inputs, and the energy content of crop products], we seek to find discernible trends for on-farm crop EUE: Are there consistent patterns in the use of machinery, fuel, and supplies (translated into energetic subsidies) by continent and country? Did those countries with higher intensification (inputs per unit area per year) in fact release land from agricultural use, as predicted by Norman Borlaug's land-sparing hypothesis (21)? Did those countries that increased agricultural area (i.e., that extensified production) keep lower intensification levels along the lines of the land-sharing, wildlife-friendly farming model hypothesis (22)? How many edible (or, more generally, usable) calories are we getting out of every calorie spent in our

Significance

Global crop production tripled during the last 50 years, mainly by an increase in yield (production/area). We show that the energy embedded in the main oil-based inputs (machinery, fuel, and fertilizers) increased worldwide at a rate at first larger, but in the last decades slower, than crop production, resulting in a recent overall improved energy-use efficiency (EUE). This was explained by advances in the nitrogen fertilizer industry, irrigation, and other technologies and perhaps some environmental changes. Our results fit the "Jevons paradox": Efficiency gains, both for EUE and land (yield), did not lead to resource savings. Just as increasing production does not guarantee alleviating hunger, technologies make land (and biodiversity) savings possible, but realizing them depends on bold political decisions.

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[1]To whom correspondence should be addressed. Email: pellegrini@agro.uba.ar.

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croplands, and how much has this ratio changed over time? We wonder whether technological change (improved genetic materials, better agronomic practices, and exploiting the synergy between the two; see ref. 23) and technology adoption were sufficiently strong to counteract the negative effects on EUE of (*i*) possible diminishing returns in crop energy efficiency and (*ii*) decreasing average soil fertility by cultivating additional suboptimal areas and by deterioration of high-quality soils. We made an effort to factor out energy efficiency improvements in the manufacturing industry, which would have acted as a confounding force, in particular those in industrial nitrogen (N) fertilizer production (19).

Results and Discussion

Intensification: Physical Data Analysis. The use of land, machinery, and supplies increased globally during 1961–2014 but at very different rates and with large differences between continents. N fertilizer was the supply with the largest worldwide increase (*ca*. 955%), and the smallest change was that of land use (10%) (Table 1). As all inputs, including irrigation water, increased for each continent at a faster pace than land did, intensification was the norm. Besides, as global crop production more than tripled during the period, these rates of fertilizer-use increase imply a marked decline in crop nutrient-use efficiency, particularly for N; in other words, there were diminishing returns on a mass basis. A comparison between continents on an energy and per-area basis is included in the next section. However, from the data in Table 1 it is clear that the relative leap in input-use during the period was much smaller for North America and Europe than for the rest of the world, which we interpret as those two continents having already embraced green revolution technologies by 1961.

Fertilizer use trends differed among continents and between nutrients. N fertilizers had the lowest relative increase in Europe (threefold) and the highest in Oceania (35-fold). The average amounts applied per hectare also showed remarkable differences: Europe and North America had the highest N use at the beginning of the study period (12.3 and 13.4 kg/ha, respectively) and were outpaced by the mainly irrigated countries (MICs; see *Supporting Information*) at the end of the period; Africa and Oceania, on the other hand, had the lowest N use during all the period (0.9 and 1.3 kg/ha, respectively). Phosphorus (P) and potassium (K) fertilizers showed a smaller relative increase than N ones (three- and fivefold, respectively), but in Latin America and Asia the rate of increase (although not use per hectare) was larger than for N. P fertilizers are based on mined rock, with a foreseeable production peak just a few decades ahead (24). For Europe, the trend of fertilizer increase was far from linear: There was an initial big increase to fight hunger after World War II, followed by a significant drop as a reaction to the emerging environmental problems (25). Fifty years later, a similar process is perhaps occurring in China (26), which in 2005 accounted for 57% (26.7 Mt) of the N used by the MIC.

Machinery stock (in mass units) and the resultant diesel fuel consumption doubled during the period and also showed large differences among continents (Table 1). Africa and Oceania had the smallest machinery stock during all the period, while North America and Europe had the largest ones. Asia and the MIC experienced the greatest increase in the machinery stock, 41-fold and 24-fold, respectively. At the global scale, the land area used for agriculture increased by 10% as the result of large increases in Latin America (111%), Africa (58%), Oceania (55%), and Asia (39%) and reductions in Europe (−18%) and North America (−12%). Irrigated land increased at a higher rate than overall land use in all regions, reflecting our classification of countries: in 2014 it was almost 50% in the MICs and less than 10% in the rest of the world as a whole.

Intensification: Energy-Based Analysis. Using the ECs detailed in *Supporting Information*, we could analyze in a common unit the contribution of fertilizers, fuel, and machinery (both construction and maintenance) to crop production for each country and continent. These inputs were generally under 5 GJ/ha/y for the beginning of the study period (except for North America) and above 5 GJ/ha/y toward the end (except for Africa) (Fig. 1). Fertilizers as a proportion of total energy input increased from 23–30% to 41–48%, and thus machinery plus fuel decreased from 70–77% to 52–59%, depending on the lifespan assumption (Fig. S1). During the 1961–2014 period, the spread of intensification was noticeable across Latin America, MICs, and Asia, while it had already happened in North America and Europe (reaching a maximum there around 1990) and has not reached Africa (Fig. 1). Oceania behaved qualitatively as North America but with much lower absolute input values because of a poorer soil endowment. Crop production increased worldwide, both on an absolute and per-area basis, but with different rates and tempos among continents compared with their growth in inputs. This led to contrasting trajectories in EUE but with generally constant or decreasing trends for those continents starting at high input levels and generally increasing trends for those starting at low input levels (Fig. 1). Thus, overall, except for Africa, EUE converged from initial values ranging between 1 and 20 toward the vicinity of 3 and 4, consistent with an almost complete globalization of agricultural inputs and practices. Our EUE estimate, translated to the common "cradle-to-gate" language,

Table 1. Agricultural land and inputs used by continent at the beginning (1961) and end (2014) of the period studied

	N fertilizer, Mt		P fertilizer, Mt		K fertilizer, Mt		Machinery, Mt		Fuel, Mt		Cultivated land, Mha		Irrigated land, Mha	
	1961	2014	1961	2014	1961	2014	1961	2014	1961	2014	1961	2014	1961	2014
Continent														
Africa	0.07	1.08	0.15	0.52	0.04	0.29	1.02	1.3	0.51	0.65	76	120	2	5
Asia	0.34	9.23	0.24	3.28	0.04	3.84	0.85	35.45	0.32	13.29	115	161	15	40
MIC	2.56	55.77	1.34	24.82	0.85	17.17	3.1	75.64	1.55	37.82	341	361	94	178
Europe	4.37	12.63	4.65	2.83	4.49	2.91	40.2	59.74	17.59	26.14	353	288	14	13
Latin America	0.28	7.32	0.27	6.42	0.14	6.26	2.85	14.71	1.25	6.43	83	175	5	18
North America	3.16	15.26	2.73	5.15	2.17	4.97	96.31	87.31	32.1	29.1	235	208	20	27
Oceania	0.04	1.4	0.59	0.91	0.05	0.23	4.93	5.24	1.64	1.75	30	47	1	3
Total	11	103	10	44	8	36	149	279	55	115	1,234	1,361	151	284
Rate of increase		×9		×4		×5		×2		×2		×1.1		×1.9

Continents exclude 12 MICs: Bangladesh, Chile, China, Egypt, India, Italy, Japan, Nepal, The Netherlands, Pakistan, Peru, and South Korea. Data for fertilizers, machinery for 1961, cultivated land (arable land, including irrigated land and permanent crops) are from FAOSTAT (20). Data for machinery for 2014 are from refs. 20, 53, and 54; also see *Supporting Information*. The data for diesel fuel are the authors' estimates using ref. 54; also see *Supporting Information*.

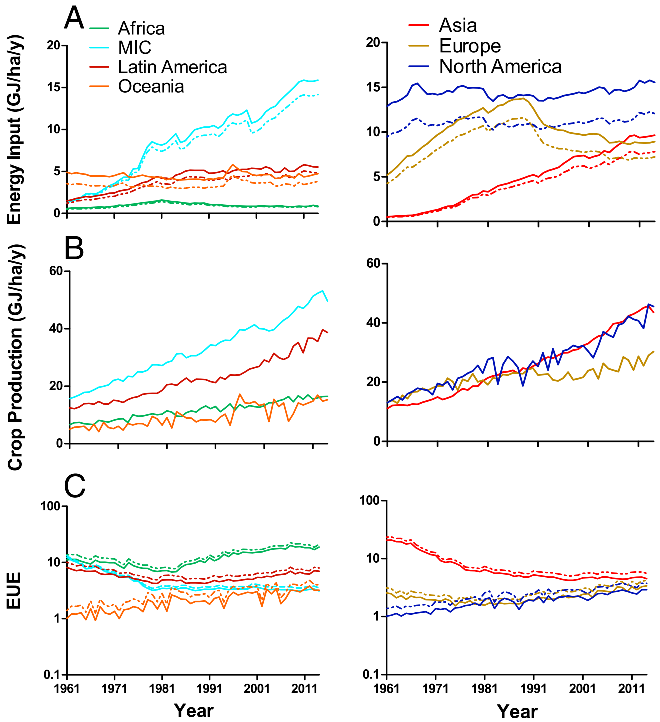

Fig. 1. (*A*) Annual energy input (GJ·ha^{-1}·y^{-1}) as the sum of fertilizers (N, P, and K), machinery (construction and maintenance), and fuel. (*B*) Total annual energy production from all crops (output; GJ·ha^{-1}·y^{-1}). (*C*) Annual EUE for each continent estimated as the ratio of crop production (GJ) to energy input (GJ) (note log scale). Solid and dashed lines in *A* and *C* are for 10- and 30-y machinery lifespans, respectively (*Supporting Information*). Data are shown for six geographical continents, excluding countries with 30% or more agricultural land under irrigation in 2005 (these are presented separately as MICs and are listed in *Materials and Methods*). Data for input, production, and land are from FAOSTAT (20); input ECs are from Table S1; crop ECs are from the FAO (*Supporting Information*).

represents an energy use of *ca*. 4–5 GJ·t^{-1}, on the order of what was found by two recent reviews (5, 19) [assuming an energy content of grains of 15 GJ/t (0.35 kcal/g), applicable to 85% of the calories produced worldwide (8, 20).]

Although all continents slowed their growth in energy inputs per hectare after the 1980s (in parallel with sinking prices for agricultural commodities), there was an almost threefold increase in total inputs from *ca*. 5 EJ for 1961 to *ca*. 13 EJ in 2014. This is equivalent to 4.5 and 2.6% of the world's primary energy supply for the beginning and the end of our study period, respectively (27). It is accepted that on-farm energy use represents by far the smallest one in the food system, below that of transport, which in turn can be several times smaller than the energy needed for heating or cooling greenhouses, refrigeration, and processing (5). Thus, despite the popularity of "food miles" (distance), a number of other life-cycle components determine our food's footprint, ranging from seasonality to soil-nutrient extraction per unit of harvested energy and protein (28). None of these can be ignored a priori when making responsible dietary choices, since many are likely to be at least as important as food miles.

For the globe, as for each continent, crop output in absolute terms was always above pooled inputs, and thus EUE was >1. Average global efficiency in the 1960s was between 2.5 and 3.5, depending on the machinery lifespan assumption, but with a clear decreasing trend toward the first half of the 1980s, followed by an increase that in the last decade reached 3.5–4.5 (green lines in Fig. 2). Such a bounce occurred because of a "breakpoint" in the rate of increase of the global agricultural energy subsidy that occurred sometime near 1980. Until then, the rate of this increase was 330–298 PJ/y, and afterwards it was 53–43 PJ/y (using 10-y and 30-y machinery lifespans, respectively), with the actual change in 1980 being ± 0.85 (SE) and ± 0.86 for 10-y and 30-y machinery lifespans, respectively (P value < 0.001) (R software, Segmented package). As a consequence of this drop in the precedent exorbitant growth of inputs and a constant increase in production output (645 PJ/y), EUE started to increase after 1980, probably now surpassing 4 (Mann–Kendall test; P value = 2×10^{-16} for both 10-y and 30-y machinery lifespans).

The overall increasing trend in EUE during the last three decades can be ascribed to several causes. There was an unmistakable effect of the improved energy efficiency of N-fertilizer synthesis, which by the 1980s had nearly doubled (Table S1), as shown by the difference between the actual EUE and those discounting that effect (green vs. yellow lines in Fig. 2). The EUE increase was not caused mainly by irrigation, since the change after 1985–1990 holds for every single continent and for the world even after removing the 12 MICs (Fig. 3, black dashed line). (Note that the increase in irrigated area for the non-MIC countries was of 49 Mha, less than 5% of the area of rainfed cultivated land) (Table 1).

The reasons for the sustained increase in EUE after discounting the positive effects of irrigation and fertilizer industry improvements can be several and are nonexclusive: genetically improved varieties and hybrids, agronomic practices and tools, "fertilization" by atmospheric carbon dioxide (which during the 1980s had already reached 350 ppm, or 23% above preindustrial levels), and associated higher water use efficiency in rainfed C3 crops. Climate change so far seems to have had mixed region- and crop-specific effects on yields, positive in some cases but mostly insignificant to negative in the 1980–2008 period (29). Finally, for Europe and North America, part of the upward EUE trend might also be attributed to a long-lasting legacy of prior fertilization (30).

Our analysis has several limitations that may have influenced EUE figures. One is the lack of dependable data for pesticides (*Supporting Information*). Moreover, a review of the most-used methods to estimate pesticide ECs warns of the risks of underestimation for chemicals introduced since 1985 (31). Our decision of using a fixed EC for fuel may have caused a bias of comparable magnitude but opposite sign (overestimation of fuel use). However, rather than hoping for these errors to cancel each other, we claim that having consistent worldwide databases for both is crucial to refine these estimates. This is also necessary for irrigation data, because, even when we managed to separate those countries with mostly rainfed agriculture, those broadly irrigated (i.e., MICs) account for *ca*. one-third of the plant-based energy output (20).

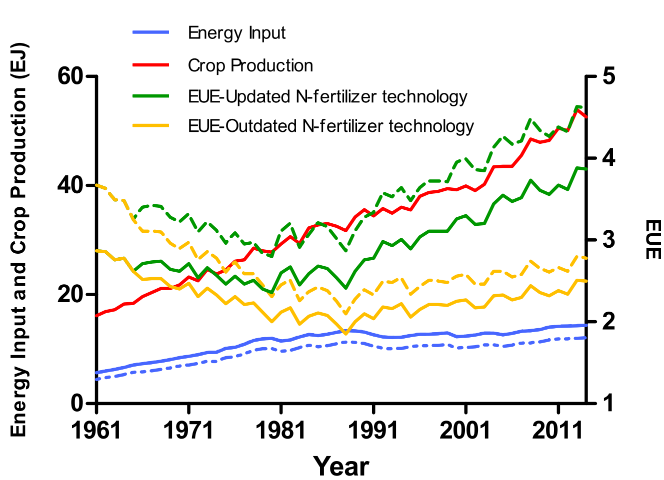

Fig. 2. Total annual energy input (in EJ), crop production (in EJ), and EUE of the 58 main crop-producing countries. "Outdated" and "Updated" N-fertilizer technology refer to industrial energy efficiency in synthesizing ammonia (*Supporting Information*). Energy input and EUE are presented for two machinery lifespan scenarios: 10 y (solid line) and 30 y (broken line).

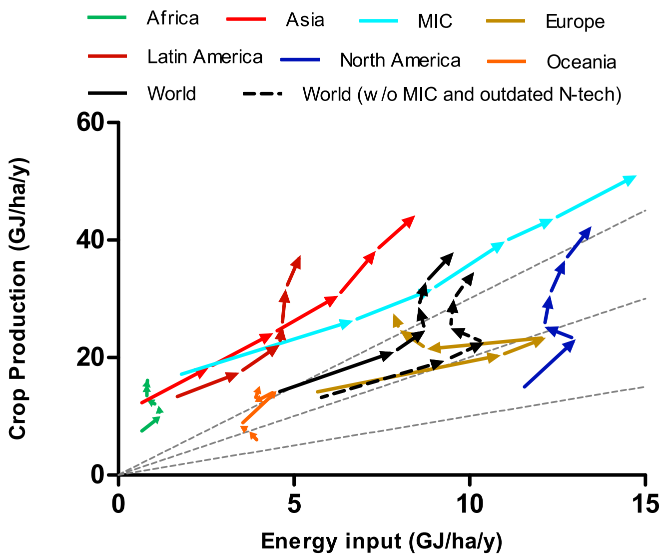

Fig. 3. Crop production as a function of energy input for the 58 main crop-producing countries (average of 10- and 30-y machinery lifespan assumption). The black dashed line represents the world excluding MICs and excluding improvements in N-fertilizer manufacturing (using outdated technology). The arrows start at the averages for 1961–1965, 1975–1980, 1985–1990, 1995–2000, and 2003–2008, and the last ends in 2010–2014. Three fixed EUE lines (3:1, 2:1, and 1:1) are presented as reference.

Intensification vs. Extensification. Our results include examples consistent with both the land-sparing and the land-sharing models, not only in terms of the number of countries but also of the net area released from or incorporated into agriculture. Of the 30 countries that kept a low intensification level or intensified later (time-averaged inputs <5 GJ/ha/y), 24 increased their cropped area (pink panels in Fig. 4); conversely, of the 28 countries with higher intensification (inputs >5 GJ/ha/y), 23 barely changed or decreased it (blue panels in Fig. 4). Even when there are exceptions (unshaded panels in Fig. 4), including very large countries such as China and the former Union of Socialist Soviet Republics (USSR), the pattern also holds when analyzed by area: Low-intensification countries in the upper left unshaded panels abandoned a total of 42.0 Mha, and those in the pink-shaded ones incorporated 177.5 Mha, leading to a net extensification of 135.5 Mha. Symmetrically, high-intensification countries in the blue panels had a combined land release of 56.6 Mha, whereas those in the unshaded ones extended their crops by 25.2 Mha, leading to a net release of 31.4 Mha. This incorporation of some areas into agriculture when others are simultaneously spared elsewhere resembles the global trend summarized by Bruinsma (32) for the 1961–2005 period, namely that for every 5 ha newly incorporated into agriculture (mainly in developing countries) 1 ha was released (mainly in developed ones). These estimates at the national level, however, should be considered an underestimation of such turnover, because it is very likely that something of the same sort is happening within each country for physical (e.g., erosion or salinization) or political (e.g., planning policies) reasons.

In our data, all continents (including MICs) are represented in the four combinations of intensification–extensification, and the pattern, as in Bruinsma (32), seems to be explained more by development stage than by geography (or irrigation). Besides, it is important to underline that a consistency with either the land-sparing or land-sharing prediction does not constitute proof of their validity as explanations. The associations highlighted by color in Fig. 4 can have different causes in different countries, even reversing the causality proposed by those hypotheses. For example, some land-poor countries may turn to intensification as their only option, and some land-rich ones may opt for extensification only, without increasing inputs. Also, the land-sparing hypothesis rests on at least two questionable assumptions: (*i*) that demand for agricultural products is inelastic, which is becoming more and more unrealistic in a globalized world where grains are increasingly used for fodder or biofuels (21), and (*ii*) that land spared from high-intensity cropping will turn to better-conserved land, which is unlikely (33), among other reasons because the options for land use are almost endless (34). Thus, successful intensification should not be regarded as a guarantee of land sparing.

Despite the apparently small increase in agricultural area on a percentage basis, expansion during the period included at least 110 million ha. This is expected to keep growing at similar rates, particularly concentrated in sub-Saharan Africa, Latin America, and some countries such as Russia and Indonesia (34, 35). Rockström et al. (36) listed land-system change as one of the main threats to planetary health and warned about our proximity to the safety boundary of *ca*. 15% of intensively used continental area. Land agricultural use interacts strongly with sustainability dimensions at a range of spatial scales, including the global one, since the rates of fertilization typical of intensive agriculture have potential for large releases of N-based greenhouse gases per hectare. However, if properly managed, associated land sparing could avoid the release of more than sufficient CO_2 to offset them (37).

Closing Remarks. Starting during the 1960s and 1970s with excessive levels of input use in North America and Europe and very low ones almost everywhere else, most of the world converged toward the present, more standardized set of agricultural inputs. This green revolution wave spread from both sides of the North Atlantic toward Asia and Latin America without fully reaching Africa. Differences among countries remain, not only because of dissimilar histories and natural constraints, which are particularly challenging in Africa (38), but also because of political decisions such as banning genetically modified organisms or fostering irrigation. Still, we observed a consistent global increase in farm-level EUE for the last 30 y that, even after discounting the substantial industrial improvements in N-fertilizer synthesis, has allowed today's farms to be as energy efficient as those at the beginning of the green revolution. Pelletier et al. (5) have argued that diminishing energy returns are not warranted in food systems. This is perhaps reasonable, given that Liebig's law of the minimum would strictly apply only to single inputs, and seems to be confirmed by our Fig. 3. However, even if our estimates for the last decades are somewhat optimistically biased, it is clear that the predictions of an unavoidable drop in EUE were not fulfilled and that the combined effect of all the factors discussed above was to counteract the expected negative trend in soil quality by intensification and extensification.

A further limitation worth mentioning is our assumption of human labor as quantitatively unimportant in energy terms. Because FAOSTAT focused on commodities, i.e., tradable agricultural products, it very likely underestimates what is produced in small farms (which is expected to be used mainly for self-consumption within the same household), where human labor can be an important subsidy. As an extreme, where it is the only subsidy, EUE needs to amount to 10–20 to make up for the inefficiency of our homoeothermic metabolism (6, 39). Small farms cannot be ignored, and for some crops they represent a sizable share of worldwide production (40). Rice, in particular, which contributes one-fifth of the calories for the average human diet, is mostly grown in farms smaller than 5 ha, with the smallest (<2 ha) contributing more than half of worldwide production. Thus, for rice, and possibly also for other food staples of regional or local importance, our analysis would underestimate the energy contribution of human labor and perhaps also that of draft animals (39).

Despite its limitations and biases, we think that our analysis is robust with respect to an increase in EUE for rainfed agriculture in commercial-scale farms. We deem it worthwhile to highlight also what has not happened in parallel with this improvement in EUE: Resources have not been saved and have not even been

% Land cleared (+) or released (-) for agriculture (1961-1965) - (2010-2014)	Average Energy Input (GJ/ha/y) (1961-2014): 0 to 3	3 to 5	5 to 10	10 to 50	> 50
-55 to -7 Land-Use Reduction		Ex USSR Syria	Bulgaria, *Chile*, Colombia, Hungary, Romania	Denmark, Finland, France, *Italy*, Poland, South Korea, Spain, Sweden, United Kingdom, U.S.A	Austria, *Japan*
-7 to +7 Small or NO Change		*Bangladesh, India, Pakistan, South Africa*	Canada, Turkey, Venezuela	Germany, Greece	*Netherlands*
+7 to +55 Extensification .	Cambodia, Morocco, Myanmar, *Nepal*, Niger, Nigeria, Philippines	Australia, Guatemala, Iran, Mexico		*China, Egypt, North Korea*	
>+55 Vast Extensification	Argentina, Bolivia, Burkina Faso, Kenya, Madagascar, Paraguay, *Peru*, Tanzania, Uganda	Brazil, Indonesia, Malaysia, Thailand	Cuba, Vietnam		

Fig. 4. Most important agricultural countries (responsible for 95% of global crop production) classified by average energy input (GJ/ha/y) and net percentage of land cleared or incorporated for agriculture. Energy input (GJ/ha/y) is the sum of fertilizers (N, P, K), machinery (construction and maintenance), and fuel from 1961–2014 (*Supporting Information*). The percentage of net land cleared or released for agriculture between 1961–1965 and 2010–2014 is the FAO's Agricultural Land and Permanent Crops average. Pink panels conform to the land-sharing hypothesis, and blue panels conform to the land-sparing one. Italics indicate generalized irrigation (MICs).

used at a constant rate. On the contrary, their consumption increased by a factor of 2.6 (Fig. 2). As counterintuitive as it seems, such a rebound effect, known as the "Jevons paradox," is a well-established principle of environmental economics (41). During the industrial revolution, William S. Jevons observed that engineering improvements leading to more efficient steam engines increased the demand for coal to power them. We have shown that, during the green revolution, agronomic improvements led to a threefold improvement in average yield ($GJ \cdot ha^{-1} \cdot y^{-1}$ or $t \cdot ha^{-1} \cdot y^{-1}$), i.e., land-use efficiency. However, instead of preventing land clearing, and much less causing the land-sparing hoped for by Norman Borlaug, the higher productivity brought about a regionally significant extensification (concentrated in Asia and Latin America) fueled by a more elastic global demand than he envisioned (21). (Although we acknowledge that land clearing would have been much larger had the increase in yields not happened; see ref. 42.) Coming from a 50-y worldwide experiment, the significance of this pattern cannot be overstated: Technological improvements make land savings possible but do not guarantee them, and in a mostly open trade market are very likely to backfire. Thus, we agree with Rudel et al. (21) that extensification can be brought to a halt only by proactive policy intervention.

Agricultural and other intensive land uses have been identified as the major global driver behind the loss of terrestrial biodiversity and ecosystem functioning (43, 44). However, extinctions can be deceptively unresponsive to land clearance for at least two reasons. One is the inherent delay in population dynamics, even after a species has diminished beyond its viable local density threshold (extinction debt) (45). Another is the positive but nonlinear relationship between terrestrial biodiversity and unfarmed area (46, 47). Thus, the detrimental effects of land use can be easily underestimated, or even overlooked, and need to be better communicated at all levels. The research community has to keep advancing knowledge, but this is not enough. We must become aware of the very limited impact that our work can have if we assume that decision makers will act according to our preferences or advice (48). On the contrary, there is a range of roles that need to be fulfilled to reach relevant audiences with better-targeted approaches and messages (49).

In sum, we have shown that on-farm technological changes have led to yield improvements at surprisingly constant, and perhaps even growing, EUE. This leaves room for optimism regarding the prospects of a sustainable intensification, particularly considering that many available proven technologies (including nonappropriable ones) have not been adopted yet (50, 51). (However, see ref. 52 for a concerned view on the slow rates of genetic improvement, development of farm-ready cultivars, and farmer's adoption.) It is also encouraging to see that intensification alone could be able to meet the projected food demand (e.g., ref. 37), but this would not necessarily mean alleviating hunger if waste is not reduced and, above all, if income equity remains at its current unacceptable levels (or if other means are not found to improve food distribution, ominously called "access"). Intensification will not avoid environmental impacts if we are not watchful and proactive regarding chemical, edaphic, and biological risks and if policy interventions to avoid simultaneous extensification are lacking. No matter how sustainable future gains in productivity per unit of land may be, in the current business-as-usual atmosphere they will not prevent further clearance and associated detrimental changes.

Materials and Methods

The countries listed in Fig. 4, responsible for 95% of the production of the 10 main crops (on an energy basis) in 2005, were selected for our analysis using the FAOSTAT database (ref. 20; last accessed, May 2017). From the same database we obtained crop production, land use, machinery, and fertilizers consumption data for each of those countries during 1961–2014. The physical quantities for outputs and inputs (mass per year) were converted to energy units using ECs from the literature. A great variability among the ECs used in agricultural energy analyses was found, so we detail our choices and their rationale in *Supporting Information*. There we use sensitivity analysis to show that the most important source of uncertainty was the choice of machinery lifespan. Since we were not able to estimate ECs for irrigation, countries in which most of their 2005 production included watering (irrigated area >30%) were treated separately as MICs: Bangladesh, Chile, China, Egypt, India, Italy, Japan, Nepal, The Netherlands, Pakistan, Peru, and South Korea.

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Supporting Information

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Country Selection

The countries responsible for 95% of the year 2005 production (energy output, e.g., grain, edible roots, and so forth) of the 10 principal crops were selected for our 1961–2014 analysis using the FAOSTAT database (ref. 1; last accessed, May 2017). Crops used for the country selection were barley, cassava, corn, palm fruit, potatoes, rice, soybean, sugar beet, sugar cane, and wheat, but then all crops were taken into account to estimate country output. An analysis by crop was beyond our reach because FAOSTAT input data are pooled at the country level. The country tally was 58–62, depending on the period. We used USSR values until 1991, and thereafter used the sum of Russia, Ukraine, Kazakhstan, Belarus, and Uzbekistan (94% of the former USSR area).

An important input for which we had very limited data was irrigation water: FAO's AQUASTAT is still developing as a worldwide long-term database for irrigated area (see ref. 2); besides, we were unable to discriminate types of irrigation (gravitational, sprinkling, or dripping) and thus were unable to resolve volume or water source (surface, deep, desalinized), and much less ECs. Therefore countries with more than 30% of their agricultural area under irrigation in 2005 were analyzed separately as MICs to avoid overestimation of EUE due to the positive effect of irrigation on crop production. Assuming that yields under irrigation at least double those with no irrigation, MICs would be countries with most of their production coming from irrigated fields. Those 12 countries are listed at the end of *Materials and Methods* and were treated as a separate "continent." Mexico was included in Latin America, instead of in North America. A permutation test [multiple response permutation procedure; MRPP; (3)] confirmed statistically significant differences in average input per hectare between the seven continents so defined as a priori groups (P value < 0.001). The list of MICs, that of main-output countries, and the identity of the 10 main crops were not influenced by the decision to use the 2005 snapshot.

Crop Production and Land Use

Data for agricultural land (arable land and permanent crops) and irrigated land were obtained from FAOSTAT and used to calculate inputs per hectare. To estimate the degree of extensification, we averaged the 2010–2014 (t2) and the 1961–1965 (t1) values of arable land and permanent crops and then estimated the percentage of net land cleared for agriculture as [(t2 – t1)/t1]100. The physical amount of cereals, cocoa, coffee, fruits, mate, oil palm, pulses, rapeseed, roots and tubers, soybeans, sugar beet, sugar cane, sunflower, tea, and vegetables produced were also obtained from FAOSTAT. Crop production values (t) were multiplied by their specific energy content (MJ/t; ref. 4) and were summed to transform all crops to a single energy value of each country's annual production (output).

Inputs

The tools and supplies included in the analyses were machinery, fuel, and fertilizers. The number of machines used in each country was obtained from the sum of tractors and harvesters and threshers from the Machinery Archive in FATOSTAT. Machinery (mass units) and fuel consumption per machine for each country were estimated using the Stout (5) standards explained below. All the countries had missing machinery data after 2003, and we used Pawlak's (6) estimations for 2005 and 2010, assuming for each country (i) a linear increase or decrease between 2003–2005 and 2005–2009 and (ii) a constant value for 2010–2014.

N, P, and K fertilizer use was obtained from FAOSTAT. The FAO's metadata on fertilizers warn against the uncritical use of the two databases covering our study period (1961–2002 and 2002–2014), due to changes in methodology. We found that the differences between the two datasets in FAOSTAT for the global use of N, P, and K fertilizers in 2002 were only 2%, 3% and 15%, respectively. Since our objective was to analyze trends, rather than precise absolute values, we used both databases (starting with the new one from 2003 onwards).

ECs

The physical quantities for outputs and inputs (mass per year) were converted to energy units using ECs from the literature (Table S1). We did not include transportation of either supplies or harvested products. Our EC choices and their rationale are given below.

Machinery and Fuel. We used the coefficients proposed by Stout (5) for machinery size and fuel consumption for each region: Machinery mass of 15 t/unit for the United States, Canada, and Australia, 8 t/unit for Latin America and Europe, and 6 t/unit for Asia and Africa. For fuel consumption we used coefficients of 5 $t \cdot unit^{-1} \cdot y^{-1}$ for the United States, Canada, and Australia, 3.5 $t \cdot unit^{-1} \cdot y^{-1}$ for Latin America and Europe, and 3 $t \cdot unit^{-1} \cdot y^{-1}$ for Asia and Africa. Although these are all obvious simplifications, none of them assumes any temporal trend and thus (unlike N-fertilizer industry efficiency) they do not alter the EUE pattern shown in Fig. 2.

We were not able to find studies of energy use in the farm machinery manufacturing industry. In fact, the only ECs used in previous agricultural analyses, and apparently the only publicly available ones, are based on car industry studies (7). We used the energy needed for manufacture (80.9 GJ/t) (7) and then added 55% of it as the energy needed for repairs (44.5 GJ/t) (8). Finally, the sum of manufacture and repairing energy was divided by the estimated lifespan (10 and 30 y, see *Sensitivity Analyses* below) to transform the energy input into an annual value (Table S1). Little variability was found for fuel EC, and an average from the literature was used (Table S1).

Fertilizers. Thanks to improvements in the Haber–Bosch technology, the energy required for ammonia industrial synthesis has noticeably decreased during the analyzed period (Table S1) (9). Also, N-fertilizer ECs are country specific as a consequence of different energy sources (gas, coal, or heavy oil). We reviewed the ECs from the literature and selected gas-based ones for all countries, except for China and India, in which the coal-based (China) and heavy oil-based (India) sources demand 1.7 and 1.3 times as much energy, respectively, as a natural gas-based process (10). As there were missing years in the literature for these two countries' ammonia synthesis energy efficiency, we multiplied the gas-based values by 1.7 in China and by 1.3 in India.

For P and K fertilizers, constant values were used for the whole period. Little information about these ECs is available, but, as a consequence of the lesser amounts used (compared with N), the impact on the total energy input is low (11). We used the average of the ECs most cited in the scientific literature (Table S1).

Sensitivity Analyses

Zegada-Lizarazu et al. (11) highlighted the great variability found among the ECs used in agricultural energy analyses. To understand how much EC choices affected estimated energy inputs, we performed a sensitivity analysis of three factors: (*i*) the delay in incorporating the latest industrial ammonia technology for N-fertilizer synthesis, (*ii*) the lifespan of farm machinery, and (*iii*) fuel consumption. For (*i*) an immediate incorporation vs. a 10-y delay was evaluated, for (*ii*) 10-, 20-, and 30-y lifespans, and for (*iii*) ±10%, 20%, and 30%. The difference in (*i*) for the world average energy input was 0.73 EJ (7% summed over the 1961–2014 period), being larger for the 10-y delay in N-technology incorporation. For (*ii*) the difference between the 10-y and 20-y machinery lifespan was 0.5 EJ (5%), the difference between the 20-y and 30-y machinery lifespan was 1.4 EJ (14%), and the difference between the 10-y and 30-y machinery lifespan was 1.9 EJ (19%). Fuel consumption uncertainty (*iii*) had a relatively minor impact on overall energy use: ±4%, 8%, and 12% for over- and underestimations of 10%, 20%, and 30%, respectively, with a negligible effect of the lifespan assumption. Results for lifespan and fuel consumption were barely affected by the delay (0–10 y) used for N-technology. We decided to work with the immediate technological incorporation (updated N-fertilizer technology) and 10 y and 30 y machinery lifespans. This allowed us to bracket input and EUE estimations in the face of the largest uncertainty found in ECs. Additionally, for Fig. 2, we performed a graphical analysis of the effect of no progress in (i.e., the use of outdated) N-fertilizer technology.

The uncertainty for the contribution of pesticides to the energy input is large, with a range of estimates between 6% and 16% (12). Although ECs are available (e.g., refs. 12 and 13), there is no worldwide long-term database of consumption at the country level. Although the FAO's pesticide database has data starting from 1990, their developers warn against the use of these data for intercountry comparisons because of inconsistencies in reports. Thus, we estimated their overall contribution to the global energy input: Fungicides, bactericides, herbicides, and insecticides (grouped in "Pesticides") consumption for our 58 selected countries was summed for each year, and the annual energy input was calculated using ECs from ref. 12. This resulted in 364 PJ for 1990 and 565 PJ for 2014, i.e., an increase of 55%. However, the relative contribution to the agricultural inputs was between 2% and 6%, with no clear-cut temporal trend. As this input is generally considered minor in terms of energy, with the possible exception of horticulture (14), and our own estimates place it between 2% and 6% of the total energy input, we excluded it from the analysis.

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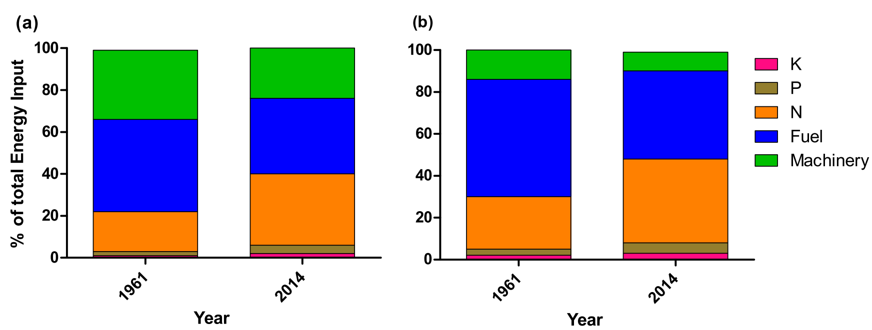

Fig. S1. Total energy input for the 58 analyzed countries classified by relative contribution of each input. (*A*) Ten-year machinery lifespan. (*B*) Thirty-year machinery lifespan.

Table S1. ECs for fertilizers, machinery, and fuel for 1961–2014

Input	Region	Period	Unit	Value	Ref(s).
N fertilizer	China	1961–1965	GJ/t N	165.24	1, 2
		1966–1979	GJ/t N	123.93	1, 2
		1980–1984	GJ/t N	88.6	3
		1985–1989	GJ/t N	69.1	3
		1990–1994	GJ/t N	66.3	3
		1995–1999	GJ/t N	61.3	3
		2000–2014	GJ/t N	40.2	3
	India	1961–1965	GJ/t N	126.36	1, 2
		1966–1978	GJ/t N	94.77	1, 2
		1979–1982	GJ/t N	75.3	4
		1983–1985	GJ/t N	71.6	4
		1986–1987	GJ/t N	68	4
		1988–1990	GJ/t N	60.7	4
		1991	GJ/t N	59.5	4
		1992–1993	GJ/t N	58.3	4
		1994	GJ/t N	55.9	4
		1995–2014	GJ/t N	55.9	4
	Rest of the world	1955–1965	GJ/t N	97.2	1
		1966–1980	GJ/t N	72.9	1
		1981–1990	GJ/t N	60.7	1
		1991–2000	GJ/t N	51.6	1
		2001–2014	GJ/t N	45.5	2
P fertilizer	World	1961–2014	GJ/t P_2O_5	14.2	5–7
K fertilizer	World	1961–2014	GJ/t K_2O	10	5–7
Machinery (10 y)	World	1961–2014	GJ/t/y	12.5	8, 9
Machinery (30 y)	World	1961–2014	GJ/t/y	4.2	8, 9
Fuel	World	1961–2014	GJ/t	45.5	10–12

Values within parentheses in Machinery indicate machinery lifespan in years.

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