A Fair Share: Doing the Math on Individual Consumption and Global Warming

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Chapter 22

Other issues: Organic vs. conventional, the problem of productivity, and corn ethanol

22.1 Organic vs. conventional

22.1.1 Overview

As a consumer one often has a choice between a product labelled "organic," and one lacking such a label, with little or no further information. So, which is better, and why? While their animating philosophies may vary, the two major practical differences between organic and conventional crops are organic prohibitions on (1) synthetic nitrogen fertilizer, and (2) synthetic pesticides. Genetically modified organisms are also prohibited, but this is far less fundamental (in my view); sewage sludge for fertilizer is, somewhat curiously, prohibited as well (this strikes me as a beneficial reuse in keeping with the organic ethos). Other prohibitions also apply for organic livestock, with hormones and antibiotics in particular prohibited (animals requiring antibiotics for acute illness must be sold into the conventional system). Thus, "organic" can encompass a wide range of farms and agricultural practices, some of which may, more or less, be "organic in name only." While it is widely supposed that these prohibitions make organic production more environmentally friendly, this is not at all obvious, either from first principles or from the data.

Organic agriculture (OA) is *clearly* less productive than conventional alternatives and thus requires appreciably more land for the same output, and is likely similar to conventional in its global warming impact (on a per-product basis) [468, 464, 465, 466, 364, 467]. On-farm, organic farms do tend to support higher levels of biodiversity per unit area, but upon adjustment for lower yields, conventional and organic farms may be similar [467]. Furthermore, organic management may also result in somewhat higher soil carbon stores, but this must be weighed against the increased land requirements, as conversion of pristine land to agriculture releases far more carbon than even the best managed farm could store [467]. Additionally, this finding could also be an artifact resulting from the transfer of organic matter, via manure, from other source fields (OA is far more reliant upon manure as a fertilizer than is conventional).

While fruits and vegetables make up a greater portion of organic sales than conventional sales, overall the organic sector (at least in the US) is reasonably similar to the larger food system in its output: livestock and poultry products remain the top single category of organic sales, and the top organic crops (by land area) are the commodities hay, wheat, corn, and soybeans. Organic animal agriculture is characterized by relatively high levels of milk and egg production, and relatively low levels of beef and chicken production, but is, overall, similar to the general system in the ratio of livestock to land base. The environmental and global warming impact of organic meat and dairy is similar to or slightly worse than the conventional analogs and thus, as a sub-system of US agriculture, OA has likely done little to mitigate the environmental harms of a food system focused on animal products.

Given the magnitude of the harms associated with pesticides (discussed in detail in Section 20.2), the most beneficial aspect of organic agriculture is likely pesticide avoidance, but it is unclear if, at a systems scale, this outweighs the costs in land. It follows that simply substituting the components of a typical conventional diet for organic alternatives is unlikely to be of much efficacy, and indeed, the effect of a broad shift to organic production methods without a concomitant shift in dietary habits (e.g. less waste and meat, especially ruminant meat) could be one of net environmental harm, mainly through increased land conversion and habitat destruction.

22.1.2 Scale of the US organic system

While organic has become far more mainstream in the last few years, global area under organic management remains minuscule, at only about 0.33% of total cultivated land area, with most concentrated in the developed world, where price premiums and, as in Europe, government subsidies support this mode of production. In the US, USDA numbers indicate that, in 2011, just 0.83% of cropland and 0.49% of rangeland (and 0.64% of all agriculture land taken together) was under organic management. As already mentioned, despite the strong association between organic and produce, the top individual organic crops are commodities, mainly hay, wheat, corn, and soy, as seen in Figure 22.1.

Eggs and dairy dominated organic animal production, with 2.78% of US milk cows, and 1.97% of laying hens raised organically, while meat animals were under-represented: 0.34% of beef cattle, 0.33% of broiler chickens, and 0.20% of turkeys were organic in 2011 (USDA ERS). While $< 1\%$ of production is organic, price premiums are such that $>4\%$ of retail sales by value are organic in the US.

22.1.3 Comparative yields

For organic agriculture to move beyond a niche product for wealthy westerners to a viable large-scale alternative system, it is necessary that it be productive enough to “feed the world.” Several meta-analyses performed in the last few years have attempted to quantify the yield gap between organic and conventional crops, and further, to determine how the yield gap varies among crop types, e.g. legumes, grains, perennials, etc. Overall, the weight of the evidence suggests that yields are appreciably lower under organic management, with the difference likely greatest for cereal grains. It must also be emphasized that these comparisons are limited to plot- and field-level comparisons, and extrapolations to higher systems levels are fraught, with multiple challenges inherent in scaling organic beyond isolated fields, as discussed presently, but for now, let us focus upon the organic:conventional *yield gap (or ratio)* in this more limited setting. Perhaps the earliest systematic review addressing the yield gap was that of Stanhill [461], who in 1990 compared the two systems using several lines of evidence and arrived at an organic:conventional yield ratio of 0.91 (i.e. organic production was 91% of conventional), averaged across 26 crop types and two animal products, but there was significant variability, and in this review, organic milk and beans actually tended to outperform conventional. In any case, this analysis is now of mostly historical interest, as the comparisons included are now many decades out of date, with some dating to the 1930s.

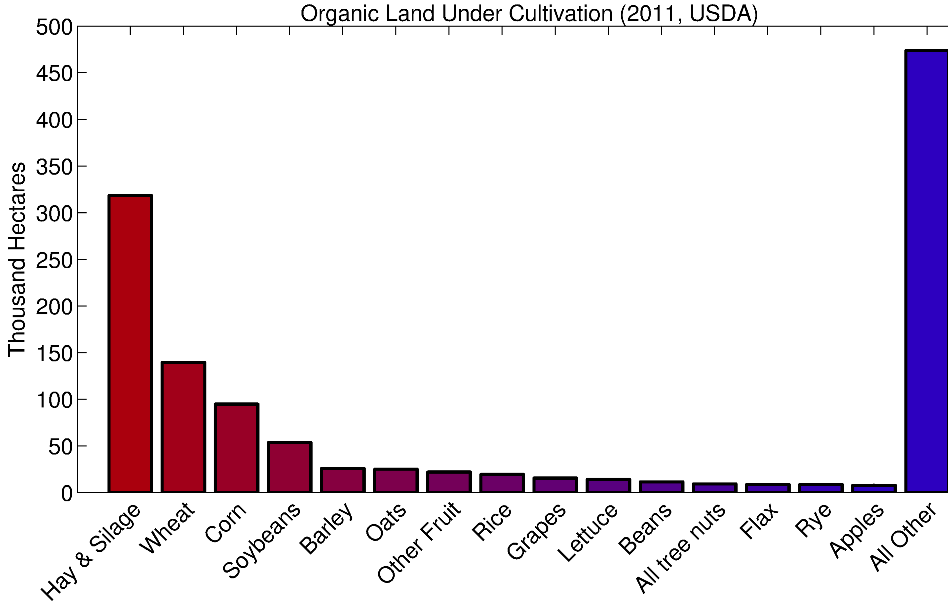

Figure 22.1: Top 15 organic crops by cultivated area, in 2011 (based on USDA ERS). Hay and other commodities clearly dominate, although the share of other crops is appreciably higher in the organic system than in the conventional one. Note that area harvested for any given crop is measured in the thousands of hectares, compared to millions under the conventional counterparts.

Later, a highly controversial 2007 analysis by Badgley et al. [460] of 293 yield comparisons concluded that, on a global basis, organic is actually the more productive mode, with an average yield ratio of 1.32 across all agricultural products, and modeling by this group further suggested a broad shift to organic could increase the global food supply. However, results varied markedly between developed countries, where the yield ratio was 0.92, and developing countries, where this ratio was a remarkably high 1.80. Applying such ratios to FAO food production statistics is the origin of the authors' conclusion that global adoption of OA could increase the food supply by >50%, but such a conclusion is deeply suspect: the favorable yield ratio in developing countries is best explained not by any intrinsic advantage to OA, but by the fact that the comparisons cited largely compared poorly productive subsistence agriculture with little or no access to inputs to optimized organic systems supplemented with large amounts of external organic inputs, e.g. off-farm manure, and could not reasonably be considered fair comparisons [462, 464, 465]. The finding that organic inputs are better than none at all is unsurprisingly and uncontroversial, and does little to inform the debate concerning the relative efficacy of OA in the developed world (or in the developing world, for that matter).

More recent meta-analyses are consistent in that, when comparing relatively comparable farming systems, the yield ratio for OA is almost uniformly <1 [468, 464, 465, 466, 364, 467]. In 2012, a systematic review by De Ponti et al. [464] excluded comparisons prior to 1985 and, notably, found only 14% of the comparisons considered by Badgley et al. met pre-defined quality criteria. Across 362 organic:conventional comparisons (mostly in North America and Europe), these authors arrived at an overall yield ratio of 0.80. They further speculated that, as many organic plots relied on very high levels of external manure input, the yield gap would likely increase when scaling up to higher system scales. Further, while they allowed that longer organic crop rotations including non-food legumes may (negatively) affect total system yields and should be adjusted for, no systematic effort was made in this respect.

Published just months after De Ponti et al, a similar work by Seufert and colleagues [465] also found organic to be less productive, with a lumped yield gap of -25% (yield ratio 0.75). Notably, the gap varied with context, and was smallest for perennials and legumes, consistent with the notion that OA is nitrogen-limited: legumes fix their own nitrogen, while perennials have larger root systems and longer growth periods that are more robust to slow or variable nitrogen availability. The gap was largest for vegetables (-33%) and cereals (-26%) and, perhaps discouragingly, was also large when the conventional and organic systems were considered most comparable, at -34%. A much larger 2015 study by Ponisio et al. [466], which used largely the same study criteria as [465], but incorporated over 1,000 comparisons, about three times more than prior works, gave a lumped yield gap of -19.2±3.7% for organic. Unlike in Seufert et al., however, no significant differences between perennials, legumes, and other crops were seen. Also noteworthy, a smaller gap was observed when organic systems were polycultures or had more rotations, but is does not appear that this analysis adjusted for the fact that a longer crop rotation also decreases the crop yield integrated over time (also addressed below). Meta-analysis focused upon wheat and maize yields in North America and Western Europe by Hossard et al. [364] suggested an average yield gap of around -30% (closer to -20% for corn, but nearly -40% for wheat), while a very recent work by Clark and Tilman also found land requirements for organic crops to be >25% higher [467].

Note that most of the above analyses are focused upon crop yields, but comparative meat and dairy yields are as or more important, given their disproportionate environmental impact. Meta-analysis by Clark and Tilman [467] suggested organic milk, dairy, and meat may require around twice the land for production, organic dairy cattle in the US produce only about 61% as much milk as their conventional counterparts [476], and my own review of individual studies on dairy and meat systems (see Sections 21.5 and 22.1.6) is also consistent with higher land requirements, largely due to lower feed conversion efficiencies in organic systems, as well as decreased yields in organic feed production [479].

In sum, the most recent and highest quality evidence suggests that, under experimental conditions, OA is about 20 to 33% less productive than conventional, on the basis of yield [468, 464, 465, 466, 364]. However, these estimates are generally plot/field-based comparisons where the organic plot often received large external inputs (mainly manure), not whole system comparisons, and Connor [463] has therefore stated, with some justice, that these are better understood as studies comparing organic and synthetic *fertilizer*, not organic and conventional *systems*, and the yield gap for an organic system could be markedly worse. These studies also do not typically adjust for sometimes longer organic crop rotations that may incorporate non-food crops for green manure (adjusting would tend to increase the yield gap), and the lower yield gap observed for longer rotations [466] may thus be essentially artifactual.

22.1.4 External inputs and organic: can an organic system be self-sustaining?

Organic systems tend to be nitrogen-limited, for several reasons [472, 465]. The most basic is the need for alternative N sources when synthetic fertilizer is eschewed, either in the form of "green manures," typically nitrogen-fixing cover crops (generally legumes) that are plowed under at the end of the season to provide nutriment for the following crop, or imported animal byproducts and manures (note that the N in manure itself must ultimately come from some soil or other). Also important is the fact there tends to be a temporal mismatch between nitrogen availability from the mineralization of organic N sources and peak demand by fast-growing annual crops. Unlike most organic amendments, the timing of soluble synthetic N applications can be more directly matched with plant demand.

The need for *external* nitrogen inputs, mainly manures and meat industry by-products (e.g. feathers, meat and bone meals [469]), is of fundamental importance and may severely limit the viability of organic agriculture as a large-scale alternative system. Indeed, in most experimental studies comparing conventional and organic yield, overall nitrogen inputs are similar in magnitude (and sometimes *greater* in the organic system), with large amounts (typically all) coming from off-farm manure. For example, Clark et al. [474] supplied organic corn and tomato beans with 150–200 kgN/Ha from composted poultry manure (comparable to conventional synthetic N application rates), and Delate et al. [475] similarly applied 157 kgN/Ha of swine manure to organic corn, identical to the conventional 157 kgN/Ha of urea.

As has been pointed out by Connor [463] and others, much of this manure and other inputs may come from conventional sources, and hence simply represent covertly processed synthetic fertilizer. Indeed, Nowak et al. [470] found that nearly all N input to 63 French farms across three agricultural districts came either from conventional sources or atmospheric N deposition (actually the major N source, which itself partially originates from volatilization of synthetic N applied to neighboring conventional farms [463]): of the N imported through manure and animal by-product fertilizers, >95% of byproduct N came from conventional sources, and 82% of manure N was conventional in origin. Once considering other nutrient inputs in the form of feedstuffs, fodders, and straw, a smaller but still hefty 66% of imported N came from conventional farms. Organic farms were also heavily reliant upon conventional agriculture for P and K fertilizers, at 73% and 53% of inputs, respectively [470].

Despite the problem of mineral nutrients possibly (or even probably) being sourced from conventional farms, we also must confront the basic fact that manure cannot hope to replace synthetic N at anything remotely approaching current use rates. Per [459], about 520,000 tonnes of manure N are applied to US fields annually, a figure wholly dwarfed by the >11 million tonnes of synthetic N spread o'er these same fields. Indeed, at the corn application rate employed by Clark et al. [474], the entire manure output of this nation's bloated animal sector would supply a scant 3.3 million hectares, just 10% of all harvested corn area and 2% of all cropland, leaving the other 98% without any inputs at all. Clearly, manure application rates in experimental organic systems are not scalable to a national system, and we must be skeptical of extrapolating such yields to any alternative hypothetical food system. Finally, it should go without saying that manure nitrogen is not some kind of "free" N source, as it must ultimately be supplied either by synthetic N fixation, or biological N fixation in some soil or other.

"Green manures," (GMs) generally either nitrogen-fixing legumes or nitrogen-scavenging grasses, are crops grown specifically to serve as a soil amendment and nutrient source for subsequent crops [471], and represent a far more viable replacement for synthetic N than manure or by-product fertilizers, although they are not without their limitations. Green manures are most typically cover crops (CC), planted during the cool season between main-season crops, especially in grain-based systems, that are then plowed under before planting the next production crop. In warmer areas, leguminous CCs can fix approximately 100–200 kgN/Ha in a season, and may obviate much or all nitrogen fertilizer need. In colder areas, however, the growth and N-fixing potential of CCs is lower, although they may still be beneficial [472]. Grass species may also be used as CCs, as they produce large amounts of biomass and also scavenge residual soil N, hence decreasing N leaching. Co-planting of grassses and legumes is a particularly beneficial practice that both effectively retains existing soil N while fixing new N. In addition to providing N, CCs have other benefits: CC biomass augments soil organic matter, and the practice of cover cropping can build soil organic carbon stores over many years [473]. Cover crops also provide habitat and suppress weed growth in subsequent main-season crops [472, 473].

While generally broadly beneficial as cover crops, green manures do have some important limitations. First, only about 10–50% of N fixed by a cover crop is available to the next crop [472]. Second, there is an asynchrony between N supplied by a CC and peak crop demand: upon incorporation into soil, CCs degrade rapidly, providing a short-lived burst of N (perhaps 6–8 weeks), which mainly predates peak demand by the subsequent main crop, although grasses tend to decay slower than legumes [472]. Third, as already mentioned, CC productivity is limited in colder areas. Fourth, in some organic rotations GMs are grown during a regular growing season, thus displacing a food crop and lowering the time-integrated productivity of the overall system. Fifth, while valuable N and C sources, green manures do not generally supply new P and K.

Finally, it should also be emphasized that green manures and cover cropping are not exclusive to organic systems, and may be (and often are) beneficially incorporated into conventional farming practices.

22.1.5 Organic livestock and animal welfare

USDA organic standards do set minimum animal welfare standards that exceed those for conventionally raised animals, and, given their philosophical leanings, many smaller organic producers appear to make animal welfare a special focus, e.g. in small pastured laying flocks. Organic livestock are required by the USDA to have access to the outdoors and direct sunlight year-round, and must not be confined in such a way that prevents free movement. In the case of poultry and eggs, the "access to outdoors" requirement has been followed by some (typically larger) egg producers more to the letter than spirit, where producers build large hen houses (with several 10,000 hens) with an adjoined outdoor screened-in "porch," thus technically meeting the requirement, but clearly not providing any meaningful pasture; close to half of organic eggs may be produced in such systems, while a new regulation, on hold at the time of this writing and with a five year phase-in period, would require a more meaningful two square feet of outdoor space for hens and do away with porches [477].

Organic ruminant production is based on pasture, with the USDA explicitly requiring that animals have access to pasture during the grazing season (no less than 120 days), and meet at least 30% of dietary dry matter intake from pasture. Therefore, organic milk systems are generally pasture-based, whereas the majority of dairy cattle raised in the US live in large confinement systems: in 2010, 73%, 17%, 6%, and 5% of milk came from conventional confinement, nonorganic semipasture-based, nonorganic pasture-based, and organic operations, respectively [476].

22.1.6 Comparative global warming impacts

In terms of global warming impact, there is no apparent benefit to organic agriculture, and for some products, the organic option may even be slightly worse. The fairly consistent conclusion across multiple studies reviewed by Mondelaers et al. [468] is that organic cropping systems tend to have lower CO_2e emissions per unit area, but, due to the generally lower productivity of OA, there is little difference between systems when CO_2e is expressed per unit product, the far more relevant metric (in my view). Recent meta-analysis by Clark and Tyler [467] similarly found a very slight, but not statistically significant trend towards increased emissions from organic systems.

Several individual analyses of animal products have found the global warming impact of organic options to be slightly higher than non-organic, mainly through somewhat lower feed conversion efficiencies. For example, Leinonen and colleagues found organic chicken and eggs to be 28% [435] and 17% [436] higher in GHG impact, respectively, and Dekker et al. [442] similarly found organic eggs to be 13–14% higher in CO_2e emissions. Multiple publications also suggest a carbon premium for organic pork production, with studies reporting increased CO_2e per kg pork on the order of 7-22% [483], 14–35% [484], or 73% [485]; Kumm [486] also reported higher CO_2e for organic vs. conventional pork, but did not provide a precise number.

Organic milk production is relatively inefficient and requires appreciably more land per unit product, but it is uncertain if its global warming impact differs significantly from conventional systems. More intensive milk production has been associated with lower kgCO_2e/kg emissions factors in some studies [479], but not in others [480, 481] (although land use more consistently decreases with intensity), emissions factors for organic and conventional milk were similar in several works [478, 480, 482], and while globally, milk production emissions are much higher outside industrialized areas, meta-analysis of mainly US and European studies [467] also showed no appreciable difference between the two methods.

As discussed extensively in Section 21.2, 100% grass-fed beef likely has a higher ecological impact, both in terms of land use and greenhouse gases, than grain-finished beef. While grass-fed or finished is not synonymous with organic, the USDA mandates access to pasture and a minimum 30% pasture feed intake for organic cows (although this requirement is waived in the final 120 days of life), so there is significant overlap.

22.1.7 Conclusions

Overall, it seems to me that minimizing pesticide, especially insecticide, applications is the most beneficial aspect of organic agriculture over conventional, although a significant body of work supports the notion that pesticide use can be markedly reduced (but not wholly eliminated) with little to no effect on yields (see Section 20.2.3). Cover crops planted between growing seasons can clearly provide significant nitrogen as well as organic matter input, but these are not limited to organic systems, and while they are unlikely to wholly replace synthetic inputs in much of the world, they can at least offset some requirements. The most environmentally friendly production system is likely a "conventional" one that does not abandon the benefits of Green Revolution technologies, but that seeks to minimize the impacts of their overuse. Moreover, such a system would be far more scalable than organic, which would quickly run into problems of organic nutrient availability if deployed at a truly global (or even national) scale. "Organic," then, defined in negative terms that (perhaps) arbitrarily prohibit potentially useful synthetic fertilizers, pesticides, antibiotics, and other inputs is ultimately more of an ideology than a scientific paradigm for environmentally friendly agriculture (see also Trewavas [487] for a discussion along these lines).

Finally, at the point of purchase, there are several products for which it may be reasonable to choose the organic option. First, produce items including grapes, apples, oranges, and tomatoes are subject to very high pesticide spraying intensities, and thus total pesticide avoided may be maximized by choosing organic versions of such products. On the other hand, while field crops such as corn and soy are sprayed at relatively low intensities, given that feed conversion ratios are on the order of 4–5 for monogastric meat [322], total upstream pesticide embodied in such meats is likely similar to heavily treated horticultural crops (and beef, with a conversion ratio approaching 40 [322], likely embodies more far pesticide than any other common food). The yield gap for legumes, such as beans and soy, may be relatively small (as observed in [465], but not in the larger analysis by Ponisio et al. [466]), and so these might also be more reasonable organic choices.

One may purchase organic animal products in the hopes of somewhat improved animal welfare, but probably at some cost to the larger environment, and the best answer is to reduce consumption, period. Indeed, unless accompanied by an absolute reduction in consumption (at least relative to a typical diet), the consumption of even organic animal products seems difficult to justify. The absolute carbon and land premium for organic monogastric products, e.g., free range organic eggs, is relatively small, and again, so long as these products are *minimized* overall, organic eggs and dairy products are probably reasonable selections. Beef is best avoided regardless, and as already discussed extensively, grass-fed beef likely carries a higher environmental cost than the grain-finished alternative. Overall, a conventionally produced diet that minimizes or eliminates animal products and waste is almost certainly vastly superior to a completely organic diet that is otherwise typically American, and organic dietary substitutions are far less meaningful than an overall dietary shift (but may be done to a limited extent as one component of a larger shift).

22.2 The problem of productivity: are higher yields truly an environmental good?

In the prior section I compared organic and conventional agriculture, and concluded that organic yields are probably lower, with a yield gap of at least 20%. This leads to the central argument in favor of conventional high-input agriculture, namely that is an efficient use of land, a finite resource. To lower the efficiency of agriculture would require the expansion of the land-base, so the argument goes, and thus conventional agriculture is a great good, preserving wild land and ecosystems that would otherwise be appropriated for Man's use. This argument is particularly salient, given that global food demand is variously projected to increase by 70% to over 100% by 2050, in the face of both global population growth and increasing worldwide demand for meat and high calorie diets, and the problem of meeting the twin demands of increased agricultural productivity and minimizing its environmental impact is clearly a fundamental one [465]. The general strategy of increasing yields via intensification with an eye toward minimizing environmental impact has been termed *sustainable intensification*, and one may consult, e.g., Garnett and colleagues [490] for a thoughtful commentary on the concept.

Indeed, it is largely true that the *per-unit* environmental impact, both in terms of land required and carbon emissions, has fallen over the latter half of the twentieth century with agricultural intensification [488, 391], and emissions factors, for animal products especially, are much lower in Western industrialized systems. For example, both GHG emissions and land use are higher in extensive pastoral beef production systems compared to intensive industrial systems [390], and FAO analyses have concluded that beef and milk emissions factors are both several times higher in the developed world compared to North America and Western Europe [387, 432]. The trend towards more intensive systems having a lower impact is likely true within the US as well: For US maize production, Grassini and Cassman [384] observed higher agricultural intensity and higher corresponding yields to result in lower GHG emissions-intensities, and as reviewed previously, more intensive animal production systems within the US also tend to save carbon on a per-product basis.

Burney and colleagues [488] constructed counterfactual scenarios to estimate how land use and GHG emissions would have differed in hypothetical worlds without the historically observed agricultural intensification between 1961 and 2005, and concluded that intensification avoided 317–590 $GtCO_2e$ over that period, or as much as one-third of humanity's historical CO_2e emissions, and suggested that improving yield is an excellent harm mitigation strategy. Forward-looking projections by Tilman et al. [489] similarly suggested that, to meet a rough doubling in global calorie and protein demand by 2050, moderate agricultural intensification in mainly developing countries could avoid 80% and 67% of the land clearing and carbon emissions, respectively, that would otherwise occur.

A related debate is that of "land-sparing" vs. "land-sharing." The notion of land-sharing is to promote farming practices that increase on-farm biodiversity and, at least to some extent, share the land with wildlife. The central problem is that such an approach tends to give lower yields, and requires more farming land overall. Land-sparing entails higher-intensity agriculture that, while less friendly to wildlife on the area actively farmed, frees, at least in principle, more land to be wholly untroubled wilderness. On the whole, so long as areas spared by high-yield agriculture are actually protected from other development, land-sparing may be the better strategy [491]. This point is key, because as discussed in just a moment, decoupled from a larger policy framework, intensification could also have the perverse effect of even greater land appropriation for farming [492].

The evidence would thus seem to fairly clearly come down upon the side of agricultural intensification and land-sparing over land-sharing. However, one possible fly in this ointment is the famous Jevons paradox, which comes from the observation of Jevons, in 1865, that increased efficiency of coal-use led to increased coal consumption. That is, as efficiency goes up, the cost of using a resource goes down, and so overall demand increases. It is worth quoting the original passages, from Chapter 7 of The Coal Question [19], at some length (emphasis in original):

> It is very commonly urged, that the failing supply of coal will be met by new modes of using it efficiently and economically. The amount of useful work got out of coal may be made to increase manifold, while the amount of coal consumed is stationary or diminishing. We have thus, it is supposed, the means of completely neutralizing the evils of scarce and costly fuel...
>
> *It is wholly a confusion of ideas to suppose that the economical use of fuel is equivalent to a diminished consumption. The very contrary is the truth...*It is the very economy of its use which leads to its extensive consumption. It has been so in the past, and it will be so in the future. Nor is it difficult to see how this paradox arises....
>
> It needs but little reflection to see that the whole of our present vast industrial system, and its consequent consumption of coal, has chiefly arisen from successive measures of economy.

The implications translate naturally to agricultural land, and I am not the first to make this comparison: Lambin and Meyfroidt [493] have reviewed the at least partially flawed of notion land-sparing through agricultural intensification expertly. As they point out, demand for staple grains (the basic provisioners of calories and protein) in a society is largely inelastic, but demand for meat and biofuels, which actually consume the majority of calories produced at the primary crop level, at least in the West, are elastic. Thus, efficiency increases may primarily act to increase production of and demand for the latter products, with little change in the area under cultivation. Furthermore, increased efficiency increases profitability, giving an incentive for expansion into more marginal lands, and therefore agricultural intensification can increase rather than decrease cropland expansion, especially within the context of a globalized agricultural trade.

The effect of agricultural intensification varies between developed and developing countries, and between agricultural systems that grow food primarily for local consumption and systems that grow cash crops for export. Increasing efficiency of local food production can indeed reduce pressure on the land, whereas increased efficiency of cash crop systems has led instead to agricultural expansion [493]. Another problem with agricultural intensification is that it may open new lands to cultivation. For example, cropland expansion into the Amazon has been facilitated by new soy varieties and heavy fertilizer and pesticide use [492]. Clearly, high yields are probably necessary, but are by no means sufficient for a relatively "green" agriculture [492].

Returning to the problem statement above, namely that agriculture must evolve to meet the demands of increasingly high-calorie and meat diets of roughly nine billion individuals by 2050 while minimizing environmental impact, the problem statement itself would seem to suggest two possible solutions beyond agricultural intensification: reduce demand for meat and high-calorie diets, or stop growing the population. Indeed, my reading of history suggests a basic problem in agriculture throughout world history that one might term the “productivity trap” [494], a seemingly never-ending ratcheting up of agricultural productivity, only to have it undermined by increasing demand and population growth. Population growth projections are always treated as *exogenous*, i.e. imposed from without, in these discussions of productivity, which simply must, it seems, expand to meet rising demand. But if productivity cannot support meat-heavy, calorie-rich diets throughout the world, then it will not; if it cannot support a population of nine billion, then it will not. The point here is that we should think of demand and supply in an integrated sense, and the answer to whether industrialized high-yielding agriculture is an environmental good is subtler than per-unit emissions or land-use factors. It is beyond me to provide a complete answer here; it remains true that, *all else equal*, a more intensive agricultural system is likely of benefit, although in reality this probably must be coupled with other policies and/or dietary shifts to be a true environmental boon.

22.3 Corn Ethanol

Analysis by the EPA concluded that corn ethanol, as produced in 2022, would generate 21–23% fewer lifecycle GHG emissions than gasoline [502]. Such conclusions motivated the 2007 US Renewable Fuels Standard (RFS2), which mandates the blending of renewable fuels into the transportation fuel supply, an ends towards which nearly half the US corn crop now goes. As we shall see, many other analyses have concluded that ethanol is actually *worse* than gasoline when it comes to greenhouse gas emissions, it saves little if any energy, and has likely driven recent large-scale agricultural expansion at the expense of natural grasslands and habitat.

Even if ethanol does achieve a 20% reduction in GHG on a per-gallon basis compared to gasoline, this would represent only a very small carbon savings overall, but at the expense of much habitat destruction and biodiversity loss. Indeed, if, hypothetically, *all* US cropland was converted to corn ethanol production, we would achieve only about a 15% reduction in light-duty vehicle emissions (i.e. I am not even counting heavy duty vehicles and freight transportation), or roughly the equivalent of increasing the average passenger vehicle fuel efficiency by 4 MPG. This cannot be emphasized enough: if ethanol were somehow scaled to the absolute theoretical maximum, it would in the best case be equivalent to increasing average fuel economy from about 22 to 26 MPG, and would require a truly vast (and likely impossible) expansion of agriculture into all remaining wild lands.

Given this, the question that remains then is, is corn ethanol, on the scale it is currently employed, valid as a minor component of a larger clean energy portfolio? Well, corn ethanol likely takes just as much fossil energy to produce as it provides, and, once the nitrous oxide emissions from agricultural soil and indirect land-use changes are properly accounted for, probably generates as many if not more greenhouse gas emissions as it offsets. Thus, no matter how you look at it, corn ethanol is disastrous. From an energetics perspective, corn ethanol is simply spinning the wheels or worse: it provides no additional energy and is probably actually a net drain on the existing fossil-based energy system. From a climate perspective, it is probably a wash or worse, and even the most optimistic assessment yields minimal overall climate benefit.

22.3.1 Energetic analysis: return on energy investment

Multiple studies have analysed corn ethanol on the basis of energy return on energy investment (EROI), a standard measure of net energy return that can be calculated for an array of energy sources, defined as the ratio,

$$\text{EROI} = \frac{\text{Energy Out}}{\text{Energy In}}. \tag{22.1}$$

An EROI of 1.0 implies that, for every unit of energy invested, a single unit of energy was extracted and thus the project was a wash; an EROI > 1 implies a net energy return on investment. The EROI for historical oil fields was around 50 (i.e. it took only 1 unit of energy to obtain 50 units), but EROI for fossil fuels tends to decrease over time as those reserves of highest quality and easiest access are spent, and extraction shifts towards lower quality resources. Tar sands, in particular, have an extremely low EROI, at perhaps 4, and oil shales have an EROI of just 7 [496]. Solar and wind have reasonably good EROIs (perhaps 10 or so for photovoltaics and closer to 20 for wind [496]) that, while lower than some fossil sources, are not subject to the same law of diminishing returns and indeed, are likely to improve with time, especially in the case of solar PV, with improving manufacturing technologies that use less raw material and energy. Note also that the energy produced by solar and wind is in the form of electricity, a higher quality form than the thermal energy contained in fossil sources.

The EROI for corn ethanol, on the other hand, hovers around 1.0, and edges above or below this magic number depending on the particular study [72]. While one may be tempted to conclude that if the EROI is greater than 1.0 then ethanol is a good idea, this is false, as emphatically pointed out by Murphy et al. [72]. Consider, at the civilization scale, EROI for a society's energy source. If it is only slightly above 1.0, then nearly all of society's energy must be used to obtain more energy, with little left over for other use. The amount of energy required to deliver a single unit of net, usable energy to society is given as

$$\frac{\text{EROI}}{\text{EROI} - 1} - 1, \tag{22.2}$$

so for an energy source with an EROI of 10, we require 0.11 units of energy to extract a single unit. The total (or gross) energy use by society then sums to 1.11 (also given as EROI/(EROI - 1)), with 90% usable. As EROI decreases, we begin to fall of the "net energy cliff," where most of society's total energy is devoted to energy extraction. If corn ethanol has an EROI of 1.3, this implies that 77% of all energy goes toward energy extraction, leaving little to support the basic infrastructure of society. Hall and colleagues [495] suggested that, as any society must gain appreciably more energy than it expends, the minimum EROI for energy sources used in support of an industrial society must be about 3; any sources with an EROI < 3 are thus subsidized by the fossil energy system.

Murphy and colleagues [72] summarized energetic inputs for corn production from five previous studies on ethanol, and under meta-analysis found an EROI of 1.07 ± 0.2. A county-level analysis by the same group across 1,287 counties suggested a national average EROI of just 1.01. A reasonable best-case EROI estimate for corn ethanol is 1.3, still far below the approximate minimum useful EROI of 3.

22.3.2 Some global warming effects of corn ethanol

- The EPA suggests an ethanol emissions factor (EF) 21–23% lower than that of gasoline, under a new gas-fired plant in 2022. My own calculations suggest an EF anywhere from 11% lower to 77% higher, using current technology, and depending upon our accounting of land use, ethanol could well be twice as bad as gasoline.
- Indirect land-use changes and N_2O from N fertilizer are major, if uncertain, factors, that undermine any benefit to ethanol.

Aside from the energetic calculus above, it is unclear if corn ethanol has a lower carbon impact than gasoline, and N_2O emissions from synthetic fertilizer and land uses changes are the major areas of controversy, as briefly discussed here. Disregarding land-use changes entirely, and using energy inputs as tabulated in [72] and [500], my own calculations suggest that, assuming a maize yield of 10 Mg/Ha and N fertilizer inputs of 157 kgN/Ha (with 1.35% evolving to N_2O), in the best case ethanol has an emissions factor of about 0.297 $kgCO_2e/kWh$, about 11% less than that of gasoline (EF 0.333 $kgCO_2e/kWh$ on LHV basis). However, a more realistic 3% conversion factor of N to N_2O gives an ethanol emissions factor of 0.3615, 9% worse than gasoline. Alternatively, even a conservative estimate of 0.05 $kgCO_2e/kWh$ due to land-use change gives an EF of 0.347 $kgCO_2e/kWh$, 4% worse than gasoline. Under a worst-case scenario, with a 5% N to N_2O factor and 0.15 $kgCO_2e/kWh$ due to land use changes, we have an ethanol EF of 0.5896 $kgCO_2e/kWh$, 77% higher than the gasoline EF.

Nitrogen fertilizer and nitrous oxide

The global warming impacts of nitrogen fertilizer in general are discussed extensively in Section 20.1.3. Crutzen et al. [348] have argued that, once extra N_2O emissions from fertilizer are accounted for, at a "proper" 3–5% conversion factor of new reactive N to N_2O, then the global warming impact of biofuels is worse than the fossil-based alternatives, even disregarding all other lifecycle factors (fertilizer, on-farm energy use, etc.). While my own calculations are not quite as dramatic, if the N to N_2O factor is indeed in the 3–5% range, then ethanol will be definitively worse than gasoline.

Land-use changes

There have been concerns for years that the expansion of biofuels may lead to clearing of carbon-rich ecosystems for new cropland, thus incurring a massive "carbon debt" that could take up to centuries to repay by biofuel use [70], as discussed already in Section 20.3. Land use change can also occur indirectly: if land already under cultivation is converted to biofuel production, new agricultural land may be cleared for those displaced crops. One of the most pessimistic, and famous, conclusions was that of Searchinger et al. [498], who calculated that the inclusion of land-use changes gave an ethanol global warming impact 93% higher than gasoline, over 30 years. Even less pessimistic projections (see below) negate any benefit to ethanol.

An additional concern, when new land is either cleared for corn ethanol production or even when other crops are displaced to produce corn, is that this new land will almost invariably be of lower quality. That is, the best and most fertile land in the optimal environment is used for production first, where the best return on investment can be expected. As production expands, marginal lands are cultivated, where yields will be lower for the same (or even greater) energy inputs. This applies at a local scale, i.e. the best fields in an area are used first, and at a regional scale, e.g., corn yields in Iowa, the prototypical corn belt state, are about 50% higher than yields in Texas [72]. Thus, even if there is some advantage to ethanol under optimal growing conditions, if its use drives the cultivation of marginal lands, the overall EROI will decrease and associated emissions will increase.

Such effects on land-use occur within a complicated economic system, and so directly quantifying the influence of biofuel production is difficult and controversial. However, several recent studies [497] make it clear that high commodity prices for corn and soy, largely attributable to biofuel demand, have driven a dramatic expansion of corn/soy cropland into formerly uncultivated grasslands, and that moreover, these lands are of marginal quality, highly vulnerable to drought and erosion. In addition to the carbon debts incurred, this obviously represents a massive loss of natural ecosystems and biodiversity.

Lark and colleagues [497] recently performed an analysis, using multiple land cover databases and satellite data, of continental US cropland changes from 2008–2012, those years immediately following the passage of the 2007 US RFS2, (again, mandating the blending of "renewable" fuels into the transportation fuel supply). They found that 2.97 million hectacres of land uncultivated since at least 2001 were converted to cropland, while 1.76 million Ha were taken out of production, for a net expansion of 1.21 million Ha. Most of the newly converted land was of marginal quality, and included significant expansion into the hilly landscapes of southern Illinois and northern Missouri, land formerly used primarily for grazing, and expansion into the panhandles of Oklahoma and Texas, land that is irrigated by the rapidly depleting Ogallala aquifer. Corn was responsible for 51% of increase in cropped area, expanded more than any other crop, with a net increase of 3.48 million Ha under cultivation, and was also the most planted on newly converted land, including 0.65 million Ha that had been grassland for at least 20 years. While other crops also were planted on new land, especially wheat, this was largely due to displacement from other areas.

Lark et al. [497] estimated perhaps 94–186 million $MgCO_2e$ attributable clearing new lands for corn and soy between 2008 and 2012, across 1.38 million Ha. Even attributing just half these emissions to corn, and supposing a very optimistic yield of 10 Mg maize per Ha over 50 years (yielding 18,850 kWh per Ha [500]), this gives at least 36.1–71.5 gCO_2e/kWh ethanol, enough to offset any GHG benefit to ethanol. Attributing all emissions to corn ethanol and amortizing over 20 years and we would have 181–358 gCO_2e/kWh ethanol, enough to nearly double the GHG impact of ethanol relative to gasoline. Qin et al. [499] also modeled soil organic carbon changes resulting from land-use changes (LUC) attributable to corn ethanol, and gave a much lower overall estimate of 7.56–33.48 gCO_2e/kWh of ethanol from LUC. However, if we suppose a yield of about 20,000 kWh/Ha/yr of ethanol, and long-term soil carbon losses equivalent to 2–3 $MgCO_2e$/yr (see Section 20.3), then we would have an additional 100–150 gCO_2e/kWh, more consistent with my inferences from [497], and with the conclusions of Searchinger et al. [498].

22.3.3 Ethanol is not scalable

While I argue that it is unlikely that ethanol provides *any* emissions benefit, even if we assume that the 21% carbon reduction estimated by the EPA in 2022 (for a *new* natural gas plant) is accurate, ethanol still provides very little net climate benefit, nor can it possibly be scaled up to provide more significant benefit. At best, with about 45% of the corn crop going to ethanol to yield almost exactly 300 billion KWh of fuel energy, we would reduce carbon emissions by 21.0 million $MgCO_2e$, equivalent to about 1.52% of the emissions attributable to gasoline consumption by personal vehicles in the US, or 0.32% of US territorial emissions. That is, if literally every square inch of Iowa were devoted to corn ethanol production, overall US emissions would decrease by barely one third of one percent!

On the other hand, suppose this crop land was simply taken out of production and converted back to native grassland. As discussed in Section 20.3.2, we could then *conservatively* expect soil carbon sequestration on the order of 0.30–0.60 MgC/Ha/yr [378], implying 17.6–35.1 million $MgCO_2e$ sequestered per year; this calculation does not include other increases in root mass, etc. Therefore, even a conservative estimate of the carbon savings from simply allowing the corn fields to revert to grassland is greater than the most optimistic estimate of the carbon offset of using this land for corn ethanol. Both carbon offsets are relatively low, but the grassland scenario would likely have other enormous ecological benefits.

While clearly not plausible, suppose the entirety of US cropland (165 million Ha) was devoted to corn ethanol, and the very optimistic 21% CO_2 reduction per gallon of ethanol was achieved. Then we should hypothetically save 217.43 million $MgCO_2e$, still less than 3.3% of overall US emissions (and likely much less, as much cropland is not well-suited to corn). Compare this to solar. A similar area of land covered in modestly efficient panels (obviously a purely hypothetical, and supposing 15% efficiency and a 75% performance factor) would generate about 17 times global electricity consumption in 2012, and over twice the global primary energy consumption, thus sending global, not just US, fossil fuel emissions to zero. Wind farming this area would give only about 4% the energy (assuming 1 W/m^2), but still yield over thrice the US's electricity consumption. Clearly, solar and wind are vastly superior to even an optimistic assessment of ethanol in particular, and biofuels in general.