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Analysis of farming systems establishes the low productivity of organic agriculture and inadequacy as a global option for food supply

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Although generally presented otherwise organic agriculture (OA) is much less productive per unit area of land than conventional agriculture (CA) for two reasons. First, because the yields of individual crops grown in OA are generally less than those in CA. Second, because the reliance in OA on organic fertilizer, *i.e.* plant and animal manures, requires that additional land grown to legumes to provide nitrogen (N) must be included in the calculation of relative productivity. Compared with the commonly used crop-yield ratios of OA/CA productivity of 0.75–0.81, new analyses of the relative food productivity of various crop- and crop-livestock systems presented here report lower values in the range 0.30–0.74 with many less than 0.5. The OA/CA system ratios are higher in less favourable areas and lower in productive areas more suited to crop intensification. The implications for food security and nature conservation place OA at a disadvantage because transformation to OA would require substantial expansion of agricultural land, *e.g.* an OA/CA ratio of 0.5, would require a doubling of area under OA to maintain equal production. By contrast, higher yields in CA reduce the demand for land in agriculture and consequently can conserve land for nature.

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INTRODUCTION

There is an appealing and widely accepted proposition that organic agriculture (OA) provides a viable alternative system of food production because it can achieve essentially equal production with organic methods as can conventional agriculture (CA) with agrichemicals, while at the same time avoiding adverse effects on environment and human nutrition from their excessive or inexpert use. Food production could be less costly and there is win-win for humanity and the environment. But the proposition cannot be supported by evidence.

In "closed" organic farms, the land is commonly rotated between crops and legume-based pastures that provide N, either accumulated in the soil during pasture or preserved as animal manure collected from stalled livestock and preserved for subsequent addition to cropland. Other OA farms, including some without livestock, import organic nutrients as animal and plant manures, the latter including residues from food chains, and more recently urban organic wastes. Although other nutrients can be locally important, the supply of nitrogen (N) becomes the dominating feature of management because it is the nutrient required in the greatest quantities and is as also the most labile. In OA, N is dominantly provided by biological nitrogen fixation (BNF) by legumes with a small contribution from atmospheric deposition, or by gradual extraction of fertility by mineralization of soil organic matter (SOM).

The problem is that the commonly accepted conclusion of quasi-equal productivity of OA is erroneous. The proponents of transformation to OA, for example[1–3] have been misled by studies that have analysed the relative yields of individual OA/CA crops but have presented the results as measures of the relative yield of complete farming systems[4–6] without attention to the greater proportion of land that must be allocated to legumes to provide the required N fertility for OA crops.

The food security equation is straightforward. Production = area × yield/unit area and land resources are in short supply because society has many other potential uses for arable land. Gradual transformation of agriculture to systems of lower productivity initially puts pressure on remaining CA to increase yield but will subsequently require expansion of agricultural land area also. Currently, OA occupies 2.5% of global agricultural area and 6% in Europe. The European Union has recently legislated to increase OA area to 25% by 2030[7], making the relative productivity of OA an important issue for consideration.

RELATIVE PRODUCTIVITY OF INDIVIDUAL CROPS

The published OA/CA yield ratios of experimental crops vary widely but show that legumes can mostly produce equal yields in either system, a consequence of BNF. The most widely used average OA/CA yield ratios for a range of non-legume crops are 0.75 ± 0.4[5], although higher values, 0.81 ± 0.4[6], promote the view that improvement is possible with more dedicated research in OA. It is, however, risky to apply the ratios to estimate OA productivity away from the situation in which they were measured. High ratios, for example, can be obtained at both high productivity with large applications of chemical fertilizer and organic manure, respectively, or at low productivity with little or no nutrient input. CA yields have increased substantially in the years since some of the ratios were established. Comparisons made at high levels of nutrient input might be interpreted as relevant potential organic yields of individual crops.

Importantly, however, experimental OA/CA crop–yield ratios are higher than farm yields of crops grown under commercial practice where other yield-reducing factors, weeds, pests, and diseases, as well as inadequate nutrient supply, may come into play. Reported results for such OA/CA crop yield ratios of well-managed crops range from 0.40 to 0.67 for cereals in England, France, and

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Sweden. Yield ratios of grain legumes (0.57–0.88) were also reduced under commercial conditions[8–10].

The OA/CA yield comparisons from experimental crops are widely used to estimate the relative productivity of OA and CA farming systems but the conclusions are erroneous. They ignore the greater limitations to yield in commercial OA but more importantly, they also ignore the larger proportion of legume area required for BNF. The ratios are also used in food-system models to calculate the mass balance of crops and pastures and hence productivity and imputed N balance. The inappropriateness of the ratios for this purpose is demonstrated by a study concluding that global transformation to OA with 20% legume area could feed the world on the current agricultural area with a modest reduction to the human diet[11]. That the ratios overestimate productivity can be deduced from the large amounts of N reportedly available for OA crops and pastures. The study set a fertilizer target of 98 Mt N/yr for CA but reported 115 Mt N/yr in manure alone for OA. That amount is far greater than possible by legume BNF on the specified area of 280 Mha[12].

OA/CA yield ratios of individual crops, experimental or commercial, cannot establish the relative productivity of OA farming systems. The required analysis is one that establishes the quantity of N available from BNF (legume area, rate, and efficiency of capture) and from that estimates the productivity of crops in the remaining area, in accordance with crop or crop-livestock systems employed.

A COMPARATIVE ANALYSIS OF FOOD PRODUCTION IN ORGANIC AND CONVENTIONAL FARMING SYSTEMS

It is well established that the only way to achieve high yields in OA is to fertilize with large amounts of composted animal manures. In the famous long-term plots at Rothamsted, UK, an annual application of 35 t/ha/yr (210 kg N/ha), the output from 3.5 cows, was required for wheat yielding 7 t/ha and extracting 140 kg N/ha in grain[13]. A minimum area of ca. 2 ha pasture would be required to feed those cows, depending upon their productivity and the availability of crop residues, so restricting the remaining crop area able to sustain high yields in OA. More generally, however, OA relies on accumulated fertility in SOM from which the rate of N release is too slow to provide sufficient N for high yield. In a well-documented rotational experiment in the Paris Basin[8], wheat yield following three years of lucerne, a record-breaking contributor of BNF, was 3.2 t/ha, closer to the 1960 yields than the regional average of 7 t/ha. High wheat yields (10 t/ha) which are achieved in France and Germany and extract 200 kg N/ha in harvested grain could not be produced without chemical fertilizer.

A complete evaluation of the relative productivity of OA and CA systems requires attention to the following questions.

- What proportion of land on individual OA farms is required in legumes to provide the N for the required yields of individual crops?
- What additional land areas do imported manures bring into consideration?
- What livestock productivity can be gained from legume-based crops and pastures to contribute to total food output?

Comparison of systems with different ranges of products also requires a single metric. Farmers mostly use financial returns obtainable at low risk to decide on farming strategy but here, for a discussion of food productivity, human metabolizable energy (HME, GJ/ha) accounts for contributions from various crops and from crop-livestock production systems with associated pastures and fodder crops. An important feature of these systems is the ability of ruminants to convert human-inedible cellulose to HME, with efficiency of 23% for milk and 5% for meat[14]. Wheat and milk provide 15 and 2.9 GJ/t, respectively. To provide context, an adequate human diet contains 3.8 GJ/yr as HME including 2.9 kg N as protein.

Two examples are presented based on data from commercial-scale farming.

CROP AND CROP-LIVESTOCK FARMS IN FRANCE

Crop and livestock productivity were estimated from detailed N balances of crop-pasture sequences on OA and CA farms in the Paris Region, France[15]. The terminology and number of farms per group are OA without livestock (OFC, 56) and with livestock (OMCL, 14), and CA without livestock (CFC, 76). Rotations in OA are typically long, often 7–9 years with various grain crops (cereals, oilseeds, and grain legumes) and legume-based fodder crops and pastures. In CA, rotations are short, often just 3 years, concentrating on grain crops, cereals, and oilseeds, with few legumes. OA farms import organic N fertilizer while CA farms import inorganic N fertilizer. Food production, estimated as human metabolizable energy (HME, MJ/ha), is for grain only in OFC and CFC farms whereas OMCL farms also produce milk derived from ruminant-digestible pasture and crop residues[16].

Total production is greater in CA than in OA but with different proportions of grain and biomass. Overall, the analysis establishes a major difference in food production (HME) between the OA (30 GJ/ha/yr) and CA systems (85 GJ/ha/y). Relative to CFC, the ratio of grain production is 0.43 and 0.32 in OFC and OMCL, respectively. Expressed as grain HME, the ratios are 0.39 and 0.27, while with milk added, the ratio of OMCL is increased to 0.35.

DAIRY FARMING IN SWEDEN

Farming in Sweden (latitude 55–68°N) is based on temperate crops, cereals (wheat, barley, oats), pulses (field pea and faba bean), oilseeds (rapeseed), and tubers (potato and turnips) and ruminant production dominantly supported by legume-based pasture, fodder crops, and crop residues. Most crops are grown in summer although there are cultivars of wheat, barley, turnip, and rapeseed that can be autumn-sown in southerly regions. Dairying is a dominant farming activity. Dairy cows spend most time in barns, so farming pays much attention to fodder conservation (grain, hay, and silage) and balancing livestock rations for adequate digestibility (crude protein content) and efficient use.

The data for this analysis were taken from government statistics[17] that report annual yields of grain crops, potato, fodder crops, and pastures on 331,970 and 1,724,790 ha of OA and CA farms, respectively, in eight S–N trending regions of decreasing temperature. Residues of grain crops were estimated by applying the average harvest index to grain yield of crop groups, 0.4 for cereals and 0.3 for pulses and oilseeds of both OA and CA. Milk production was estimated from available grown fodder, supplemented as needed with available grain, for alternative ruminant-feeding strategies of adequate protein content. The analysis uses HME in milk plus remaining grain (GJ/ha) as the unifying parameter for comparison of yield of the eight regional crop-livestock production systems. Production from south to north decreases from 29 to 10 GJ/ha in OA and 82–18 GJ/ha in CA while the proportional contribution of milk increases in OA but decreases in CA.

Regional OA/CA values range widely by region (0.30–0.74) from south to north with a strong inverse relationship to the regional yield of CA. In a northward trend, lower temperatures reduce the length of the growing season, crop choice and yield but increase OA/CA ratios. OA does relatively better in the north where farming is restricted to pasture production and a few hardy cereal crops. By contrast, OA/CA yield ratios are lower in the south where conditions are more favourable for intensification and diversification of cropping and the yield of individual crops can respond to greater N supply.

DISCUSSION

Issues from these two examples relate to the relative productivity of OA systems generally.

The first is that OA/CA system ratios are always less than unity and respond to both the environment and the cropping system. There is no single ratio of wide application. The Swedish example established an increasing OA/CA ratio in response to decreasing temperature and length of growing season. The important generality is that CA can be intensified in most environments by increasing N fertility but OA less so because that requires a greater allocation of farm area to the legume. Intensification of CA cropping, and higher yields, allow more and different crops to exploit advances in production technology and markets for products.

The second emphasizes the important role of ruminant livestock in the management and productivity of OA generally. This is seen in both examples. Ruminants convert human-inedible pastures and crop residues, supplemented with grain as necessary, efficiently to human food. High crop yields are only possible in OA by application of manure in large quantities that can release more N to crops than can mineralization of SOM. However, analysis reveals that an animal-manure-based OA system was not a feasible solution in 2000[13] as it was at the beginning of the 20th century when the population was 1.6b. Without N fertilizer, it is not possible to feed the current world. The solution must be found in a balance that uses ruminants optimally to benefit food production, pasture productivity, BNF and N cycling along with N fertilizer. Animal manures are difficult to use efficiently because of variable nutrient composition. Also, when used alone in amounts to supply sufficient N to support high crop yield, they apply excessive amounts of other important nutrients, notably phosphorus, and potassium[18]. Modern crop management requires careful attention to nutrient application and balances that cannot easily be a feature of OA.

Finally, regarding the use of OA/CA ratios. Only values at the farming system level can, along with productivity data, contribute to the debate about the future of agricultural practice and food security. System values are smaller than those for individual crops, so a defensible outlook is less optimistic for OA than has been widely accepted. Food system models must be evaluated against measured responses at farm and regional levels. In the French example for the Paris region, the estimated OA/CA farm ratios are 0.27–0.39 whereas in Sweden, in regions of mostly smaller productivity, they range from 0.30 to 0.71 with a value <0.5 for the four productive southern regions. In both cases signalling the need for more than doubling of OA area to maintain production comparable with CA.

CONCLUSIONS

Prior to 2007, and the publication of a paper presented at an FAO conference[4], it was commonly accepted that limited N supply from component legumes would restrict OA systems to feeding a world of 3–4 billion[19,20] and also that food supply for half of the then population of 6 b depended on the use on N fertilizer[21]. The alternative view of quasi-equivalent OA and CA production potential was then developed by further comparisons of yields of experimental crops grown with organic (OA) or chemical fertilizers (CA), with[5,6] being the most cited. This conclusion is erroneous because it ignores the additional land, on the farm or elsewhere, required for the production of the required organic manures. The appropriate analysis must be made at the system level. The wrong conclusion has, however, captured the minds of 'transformationists'[1–3] who continue to use it to successfully promote OA and related movements, despite many analyses to the contrary[12,13,16,20–27]. Not even the collapse of Sri Lankan agriculture in 2020 following an ill-informed decision to go organic by preventing imports of fertilizers and pesticides has dimmed the vision of 'transformationists'. The decision was revoked in 2021 following widespread food shortage (rice production), loss of export potential (tea), and rapid inflation.

When it comes to food production, OA falls well below CA. There is no single ratio but rather a response to site productivity. In marginal areas with short or disrupted growing seasons due to low temperatures or drought where CA crop yields are smaller, OA requires relatively less extra land for equal production. On the other hand, in areas more favourable to crop intensification, conversion of 1 ha of CA can require 2–3 ha of OA for equal human food production. Land-use efficiency will be reduced in inverse proportion. Herein is the major disadvantage of the expansion of OA to food security and nature conservation.

The obvious alternative that high agricultural productivity is essential to spare land for nature has been long evident[28] but the need for it is clearly much greater than is widely accepted. The focus in OA to increase biodiversity with long diverse rotations and intercrops would have negligible benefit compared with the loss of new land converted to agriculture to maintain global food security. Schemes and subsidies to encourage the expansion of OA have clearer, sharper limits once the discussion changes from "negligible" to "large" productivity differences between OA and CA and the consequent large increases in the land area required to feed a currently large (8.1b), and still expanding, population.

Finally, more and better studies of the productivity and environmental sensitivity of complete production systems, both organic and conventional, are required. All require high inputs, especially of N, if they are to sustain high yields. Most CA systems rely partly on BNF to provide N fertility, but high yields can only be sustained in OA with large applications of animal manure, a particularly land-hungry resource. Legumes have an important role in both systems, so management techniques are required to obtain the best results from BNF in situ or when added as organic fertilizers by reducing large N losses in manure treatment, storage and application. This draws attention to the importance and need for more studies and development of crop-ruminant livestock systems able to produce food as well as BNF from legume-based forage and reduce greenhouse gas emissions as a potent cause of global warming. Equally, the formulation and application of mineral fertilizers must be improved to increase the efficiency of use and reduce loss to the environment.

To increasing calls for OA to accept the benefits from biotechnology in breeding new cultivars for disease- and pest-resistance and greater yield[29], one could add acceptance of N fertilizer. It carries no perceived health risks as does the use of agrichemicals to control pests and diseases.

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D.J.C. designed the arguments and wrote the article.

COMPETING INTERESTS

The author declares no competing interests.

ADDITIONAL INFORMATION

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