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Organic agriculture and the global food supply

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Abstract

The principal objections to the proposition that organic agriculture can contribute significantly to the global food supply are low yields and insufficient quantities of organically acceptable fertilizers. We evaluated the universality of both claims. For the first claim, we compared yields of organic versus conventional or low-intensive food production for a global dataset of 293 examples and estimated the average yield ratio (organic : non-organic) of different food categories for the developed and the developing world. For most food categories, the average yield ratio was slightly <1.0 for studies in the developed world and >1.0 for studies in the developing world. With the average yield ratios, we modeled the global food supply that could be grown organically on the current agricultural land base. Model estimates indicate that organic methods could produce enough food on a global *per capita* basis to sustain the current human population, and potentially an even larger population, without increasing the agricultural land base. We also evaluated the amount of nitrogen potentially available from fixation by leguminous cover crops used as fertilizer. Data from temperate and tropical agroecosystems suggest that leguminous cover crops could fix enough nitrogen to replace the amount of synthetic fertilizer currently in use. These results indicate that organic agriculture has the potential to contribute quite substantially to the global food supply, while reducing the detrimental environmental impacts of conventional agriculture. Evaluation and review of this paper have raised important issues about crop rotations under organic versus conventional agriculture and the reliability of grey-literature sources. An ongoing dialogue on these subjects can be found in the Forum editorial of this issue.

Key words: organic agriculture, conventional agriculture, organic yields, global food supply, cover crop

Introduction

Ever since Malthus, the sufficiency of the global food supply to feed the human population has been challenged. One side of the current debate claims that green-revolution methods—involving high-yielding plant and animal varieties, mechanized tillage, synthetic fertilizers and biocides, and now transgenic crops—are essential in order to produce adequate food for the growing human population[1–4]. Green-revolution agriculture has been a stunning technological achievement. Even with the doubling of the human population in the past 40 years, more than enough food has been produced to meet the caloric requirements for all of the world's people, if food were distributed more equitably[5]. Yet Malthusian doubts remain about the future. Indeed, given the projection of 9 to 10 billion people by 2050[6] and the global trends of increased meat consumption and decreasing grain harvests per capita[4], advocates argue that a more intensified version of green-revolution agriculture represents our only hope of feeding the world. Another side of the debate notes that these methods of food production have incurred substantial direct and indirect costs and may represent a Faustian bargain. The environmental price of green-revolution agriculture includes increased soil erosion, surface and groundwater contamination, release of greenhouse gases, increased pest resistance, and loss of biodiversity[7–14]. Advocates on this side argue that more sustainable methods of food production are essential over the long term[15–17].

If the latter view is correct, then we seem to be pursuing a short-term solution that jeopardizes long-term environmental sustainability. A central issue is the assertion that alternative forms of agriculture, such as organic methods, are incapable of producing as much food as intensive conventional methods do[1,3,5]. A corollary is that organic agriculture requires more land to produce food than conventional agriculture does, thus offsetting any environmental benefits of organic production[18]. Additionally, critics have argued that there is insufficient organically acceptable fertilizer to produce enough organic food without substantially increasing the land area devoted to agriculture[3].

Here, we evaluate the potential contribution of organic agriculture to the global food supply. Specifically, we investigate the principal objections against organic agriculture making a significant contribution—low yields and insufficient quantities of organic nitrogen fertilizers. The term 'organic' here refers to farming practices that may be called agroecological, sustainable, or ecological; utilize natural (non-synthetic) nutrient-cycling processes; exclude or rarely use synthetic pesticides; and sustain or regenerate soil quality. These practices may include cover crops, manures, compost, crop rotation, intercropping, and biological pest control. We are not referring to any particular certification criteria and include non-certified organic examples in our data.

Methods

We compiled data from the published literature about the current global food supply, comparative yields between organic and non-organic production methods, and biological nitrogen fixation by leguminous crops. These data were the basis for estimating the global food supply that could be grown by organic methods and the amount of nitrogen that could become available through increased use of cover crops as green manures.

Estimation of the global food supply

Estimation of the global food supply grown by organic methods involved compiling data about current global food production, deriving ratios of the yields obtained from organic versus non-organic production methods, and applying these yield ratios to current global production values.

Global food production. Summary data from the Food and Agricultural Organization (FAO) for 2001[19] document the current global food supply—grown primarily by conventional methods in most of the developed world and primarily by low-intensive methods in most of the developing world. The FAO provides estimates of the current food supply in 20 general food categories[19] which we modified for our study. We combined three pairs of categories (into sugars and sweeteners, vegetable oils and oilcrops, meat and offals). We omitted from consideration three categories (spices, stimulants, and 'miscellaneous'), because they contribute few calories and little nutritional value to the daily diet and lack comparative data for organic versus non-organic production. In addition, we reported data for seafood and 'other aquatic products' but did not estimate yield ratios for these categories, since most of these foods are currently harvested from the wild. Alcoholic beverages were reported since they contribute significantly to the average daily caloric intake, but no assessment of organic yields was made. The data presented for yield ratios pertain to ten categories covering the major plant and animal components of human diets.

Food-production data of the FAO include both commercial and domestic production and exclude losses during harvest. Pre-harvest crop losses are not included in the estimates; these losses may be substantial[20] but are not necessarily more serious for organic production, since a host of methods is available for managing pests[21,22]. For each country or region, the FAO data for the food supply available for human consumption take into account food production, exports, imports, and stocks, as well as losses of production to become livestock feed, seed, or waste[19]. 'Waste' refers to post-harvest loss during storage, transport, and processing. We compiled this information for the world, for developed countries, and for developing countries, following the FAO classification of countries as developed or developing.

Deriving yield ratios. We estimated the global organic food supply by multiplying the amount of food in the current (2001) food supply by a ratio comparing average organic : non-organic yields. Comparisons of organic to non-organic production are available for many plant foods and a few animal foods. For each of 293 comparisons of organic or semi-organic production to locally prevalent methods under field conditions, the yield ratio is the ratio of organic : non-organic production. A ratio of 0.96, for example, signifies that the organic yield is 96% that of the conventional yield for the same crop. The comparisons include 160 cases with conventional methods and 133 cases with low-intensive methods. Most examples are from the peer-reviewed, published literature; a minority come from conference proceedings, technical reports, or the Web site of an agricultural research station. Like Stanhill's 1990 survey of organic and conventional production[23], our data include numerous comparisons from paired farms and controlled experiments at research stations. The studies range in observation length from a single growing season to over 20 years. Despite the observation that yields following conversion from conventional to organic production initially decline and then may increase with time[24,25] (but see ref. 23), we included studies regardless of duration. All of Stanhill's examples (which are included here) were from the developed world, whereas our dataset also includes diverse examples from the developing world. No attempt was made to bias the results in favor of organic yields; many examples from developed and developing countries exhibit low comparative yields. We avoided generalizations based on country-wide or regional average yields by organic or conventional methods. Some examples are based on yields before and after conversion to organic methods on the same farm.

Table 1. Average yield ratio (organic : non-organic) and standard error (S.E.) for ten individual food categories recognized by the FAO[19] and three summary categories. Average yield ratio based on data from 91 studies (see Appendix 1 for data and sources). (A) All countries. (B) Developed countries. (C) Developing countries.

	(A) World			(B) Developed countries			(C) Developing countries		
Food category	***N***	**Av.**	**S.E.**	***N***	**Av.**	**S.E.**	***N***	**Av.**	**S.E.**
Grain products	171	1.312	0.06	69	0.928	0.02	102	1.573	0.09
Starchy roots	25	1.686	0.27	14	0.891	0.04	11	2.697	0.46
Sugars and sweeteners	2	1.005	0.02	2	1.005	0.02			
Legumes (pulses)	9	1.522	0.55	7	0.816	0.07	2	3.995	1.68
Oil crops and veg. oils	15	1.078	0.07	13	0.991	0.05	2	1.645	0.00
Vegetables	37	1.064	0.10	31	0.876	0.03	6	2.038	0.44
Fruits, excl. wine	7	2.080	0.43	2	0.955	0.04	5	2.530	0.46
All plant foods	266	1.325	0.05	138	0.914	0.02	128	1.736	0.09
Meat and offal	8	0.988	0.03	8	0.988	0.03			
Milk, excl. butter	18	1.434	0.24	13	0.949	0.04	5	2.694	0.57
Eggs	1	1.060		1	1.060				
All animal foods	27	1.288	0.16	22	0.968	0.02	5	2.694	0.57
All plant and animal foods	293	1.321	0.05	160	0.922	0.01	133	1.802	0.09

We grouped examples into ten general food categories and determined the average yield ratio for all cases in each food category. For the complete dataset and sources, see Appendix 1. Table 1 presents the average yield ratios of these food categories for all studies combined (the world), studies in developed countries, and studies in developing countries. If no data were available (e.g., tree nuts) for estimating global organic production, then we used the average yield ratio for all plant foods, or all animal foods where relevant. For individual studies in which several yield ratios were reported for a single crop (e.g., 0.80–2.00) grown under the same treatment, we took the average as the value for the study. When different treatments were described, we listed a value for each treatment. Averaging the yield ratios across each general food category reduced the effects of unusually high or low yield ratios from individual studies. As these studies come from many regions in developed and developing countries, the average yield ratios are based on a broad range of soils and climates. The average yield ratio is not intended as a predictor of the yield difference for a specific crop or region but as a general indicator of the potential yield performance of organic relative to other methods of production.

Studies in the global south usually demonstrate increases in yields following conversion to organic methods (Table 1C), but these studies are not comparable with those in the developed world. At present, agriculture in developing countries is generally less intensive than in the developed world. Organic production is often compared with local, resource-poor methods of subsistence farming, which may exhibit low yields because of limited access by farmers to natural resources, purchased inputs, or extension services. While adoption of green-revolution methods has typically increased yields, so has intensification by organic methods[26]. Such methods more often result in non-certified than in certified organic production, since most food produced is for local consumption where certification is not at issue[27]. Data from these studies are relevant for our inquiry, which seeks quantitative comparisons between organic production and prior methods, whether by conventional or subsistence practices, since both prevailing methods contribute to global food production.

Estimating the global food supply. Using the average yield ratio for each food category, we estimated the amount of food that could be grown organically by multiplying the amount of food currently produced times the average yield ratio (Tables 2 and 3). Following the FAO methodology[19], this estimate was then proportionally reduced for imports, exports, and losses (e.g., Table 2, column D) to give the estimated organic food supply after losses (e.g., Table 2, column G), which is the food supply available for human consumption. We assumed that all food currently produced is grown by non-organic methods, as the global area of certified organic agriculture is only 0.3%[28].

We constructed two models of global food production grown by organic methods. Model 1 applied the organic : non-organic (conventional) yield ratios derived from studies in developed countries to the entire agricultural land base (Table 2). This model effectively assumes that, if converted to organic production, the low-intensity agriculture present in much of the developing world would have the same or a slight reduction in yields that has been reported for the developed world, where green-revolution methods now dominate. Model 2 applied the yield ratios derived from studies in the developed world to food production in the developed world, and the yield ratios derived from studies in the developing world to food production in the developing world (Table 3). The sum of these separate estimates provides the global estimate.

Table 2. Actual (2001) food supply and estimates for Model 1. Data for world food supply from FAO Statistical Database[19].

(A) Food category	**(B) Actual world food production**	**(C) Actual food supply after losses**	**(D) Supply as proportion of production (C/B)**	**(E) Average yield ratio (Table 1)**	**(F) Estimated organic food production (B × E)**	**(G) Estimated organic food supply after losses (D × F)**
Units	**1000 Mg**	**1000 Mg**			**1000 Mg**	**1000 Mg**
Grain products	1,906,393	944,611	0.50	0.928	1,769,133	876,599
Starchy roots	685,331	391,656	0.57	0.891	610,630	348,965
Sugars and sweeteners	1,666,418	187,040	0.11	1.005	1,674,917	187,975
Legumes (pulses)	52,751	32,400	0.61	0.816	43,044	26,438
Tree nuts	7,874	7,736	0.98	0.914[1]	7,213	7,070
Oil crops and vegetable oils	477,333	110,983	0.23	0.991	472,559	109,984
Vegetables	775,502	680,802	0.88	0.876	679,340	596,383
Fruits, excl. wine	470,095	372,291	0.79	0.955	448,940	355,538
Alcoholic beverages	230,547	199,843	0.87			
Meat and offal	252,620	247,446	0.98	0.988	249,588	244,476
Animal fats	32,128	19,776	0.62	0.968[2]	31,100	19,143
Milk, excl. butter	589,523	479,345	0.81	0.949	559,457	454,898
Eggs	56,965	50,340	0.88	1.060	60,383	53,360
Seafood	124,342	95,699	0.77			
Other aquatic products	10,579	8,514	0.80			
Average for all foods				0.922		

[1] Average yield ratio for all plant foods (developed countries) was used, since no comparative yield data were available for this food category.

[2] Average yield ratio for all animal foods (developed countries) was used, since no comparative data were available for this food category.

Mg = megagram = metric ton.

In Model 1, the standard error of the estimate was calculated for an affine transformation (i.e., rescaled to world food production)[29]. In Model 2, the estimated global organic food production was the sum of two regional calculations—the yield ratios from the developed world times the current food production in the developed world and the yield ratios from the developing world times the current food production in the developing world. The standard error of the global estimate was determined for the sum of two independent random variables[29].

For Model 2, we did not adjust for the amount of imported food in each food category. These amounts ranged from 4.9 to 75.8% (imported as a proportion of total food supply before losses) for the developed-world food supply and from 0.7 to 22.7% for the developing-world food supply[19]. Adjusting for imports in Model 2 would elevate slightly to greatly the estimates of the organic food supply in developed countries (Table 3, column F, because a proportion of the actual food supply would be multiplied by the higher average yield ratios for developing countries) and would diminish slightly the estimates of the organic food supply in the developing world (Table 3, column K, because a proportion of the actual food supply would be multiplied by the lower average yield ratios for the developed world). The overall results would be qualitatively similar.

Additional model assumptions. Both models were based on the pattern of food production and the amount of land devoted to crops and pasture in 2001. The models estimate the kinds and relative amounts of food that are currently produced and consumed, including the same pattern of total and per-capita consumption of meat, sugars, and alcoholic beverages. Additional assumptions include (1) the same proportion of foods grown for animal feed (e.g., 36% of global grain production), (2) the same proportion of food wasted (e.g., 10% of starchy roots), and (3) the same nutritional value of food (e.g., for protein and fat content in each food category), even though changes in some of these practices would benefit human or environmental health. Finally, we made no assumptions about food distribution and availability, even though changes in accessibility are necessary to achieve global food security. These assumptions establish the boundary conditions for the models but are not intended as an assessment of the sustainability of the current global food system.

Calories per capita

The calories per capita resulting from Models 1 and 2 were estimated by multiplying the average yield ratios (organic : non-organic) in each food category by the FAO estimate of per-capita calories currently available in that food category[19].

Nitrogen availability with cover crops

The main limiting macronutrient for agricultural production is biologically available nitrogen (N) in most areas, with

Table 3. Actual (2001) food supply and estimates for Model 2. Data for world food supply from FAO Statistical Database[19]; data for yield ratios from Table 1.

(A) Food category	(B) Actual food production	(C) Actual food supply after losses	(D) Food supply as proportion of production	(E) Av. yield ratio	(F) Est. organic food supply after losses	(G) Actual food production	(H) Actual food supply after losses	(I) Food supply as proportion of production	(J) Av. yield ratio	(K) Est. organic food supply after losses	(L) World, est. organic food supply after losses (F + K)
	---------------------------------Developed countries-----------------------------					--------------------------------Developing countries---------------------------					World
Units	1000 Mg	1000 Mg		Ratio	1000 Mg	1000 Mg	1000 Mg		Ratio	1000 Mg	1000 Mg
Grain products	879,515	178,973	0.20	0.928	166,087	1,026,878	765,638	0.75	1.573	1,204,348	1,370,435
Starchy roots	176,120	96,754	0.55	0.891	86,207	509,211	294,902	0.58	2.697	795,352	881,559
Sugars and sweeteners	332,987	56,274	0.17	1.005	56,555	1,333,430	130,766	0.10	1.736[4]	227,010	283,565
Legumes (pulses)	15,122	1,679	0.11	0.816	1,370	37,628	30,721	0.82	3.995	122,729	124,099
Tree nuts	2,194	3,336	1.52[1]	0.914[2]	3,049	5,680	4,400	0.77	1.736[4]	7,638	10,687
Oil crops and veg. oils	175,591	25,316	0.14	0.991	25,089	301,741	85,667	0.28	1.645	140,921	166,010
Vegetables	163,815	150,127	0.92	0.876	131,511	611,687	530,675	0.87	2.038	1,081,516	1,213,027
Fruits, excl. wine	123,276	108,224	0.88	0.955	103,354	346,818	264,067	0.76	2.530	668,088	771,443
Alcoholic beverages	122,376	110,827	0.91			108,172	89,016	0.82			
Meat and offal	111,595	106,865	0.96	0.988	105,583	141,024	140,581	1.00	1.802[5]	253,327	358,909
Animal fats	21,420	10,881	0.51	0.968[3]	10,533	10,708	8,895	0.83	1.802[5]	16,029	26,561
Milk, excl. butter	347,782	260,699	0.75	0.949	247,404	241,742	218,645	0.90	2.694	589,030	836,434
Eggs	18,645	16,697	0.90	1.060[3]	17,699	38,320	33,643	0.88	1.802[5]	60,625	78,323
Seafood	30,894	30,401	0.99			93,447	65,298	0.70			
Other aquatic products	958	234	0.24			9,621	8,280	0.86			

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[1] Ratio is greater than 1.0 because of imports. All values in column (C) include imports but these are typically a small proportion of food production; for tree nuts, however, about one-third of the supply for the developed world is imported from the developing world.

[2] Average yield ratio for all plant foods (developed countries) was used, since no comparative yield data were available for this food category.

[3] Average yield ratio for all animal foods (developed countries) was used, since no comparative yield data were available for this food category.

[4] Average yield ratio for all plant foods (developing countries) was used, since no comparative yield data were available for this food category.

[5] Average yield ratio (developing countries) for all plant and animal foods was used, since no comparative yield data were available for this food category; the average for all foods was a more conservative estimate than the average for animal foods alone.

phosphorus limiting in certain tropical regions[30]. For phosphorus and potassium, the raw materials for fertility in organic and conventional systems come largely from mineral sources[31] and are not analyzed here.

Nitrogen amendments in organic farming derive from crop residues, animal manures, compost, and biologically fixed N from leguminous plants[32]. A common practice in temperate regions is to grow a leguminous cover crop during the winter fallow period, between food crops, or as a relay crop during the growing season. Such crops are called green manures when they are not harvested but plowed back into the soil for the benefit of the subsequent crop. In tropical regions, leguminous cover crops can be grown between plantings of other crops and may fix substantial amounts of N in just 46–60 days[33]. To estimate the amount of N that is potentially available for organic production, we considered only what could be derived from leguminous green manures grown between normal cropping periods. Nitrogen already derived from animal manure, compost, grain legume crops, or other methods was excluded from the calculations, as we assumed no change in their use. The global estimate of N availability was determined from the rates of N availability or N-fertilizer equivalency reported in 77 studies—33 for temperate regions and 44 for tropical regions, including three studies from arid regions and 18 studies of paddy rice. N availability values in kg ha^{-1} were obtained from studies as either ‘fertilizer-replacement value,’ determined as the amount of N fertilizer needed to achieve equivalent yields to those obtained using N from cover crops, or calculated as 66% of N fixed by a cover crop becoming available for plant uptake during the growing season following the cover crop[34]. The full dataset and sources are listed in Appendix 2. We estimated the total amount of N available for plant uptake by multiplying the area currently in crop production (but not already in leguminous forage production—large-scale plantings of perennial legume systems) by the average amount (kg ha^{-1}) of N available to the subsequent crop from leguminous crops during winter fallow or between crops (Table 4, Appendix 2).

Results and Discussion

Estimates of food and caloric production under organic agriculture

Figure 1 compares the estimates from Models 1 and 2 to the current food supply. According to Model 1, the estimated organic food supply is similar in magnitude to the current food supply for most food categories (grains, sweeteners, tree nuts, oil crops and vegetable oils, fruits, meat, animal fats, milk, and eggs). This similarity occurs because the average yield ratios for these categories range from 0.93 to 1.06 (Figure 1, Tables 1B and 2). For other food categories (starchy roots, legumes, and vegetables), the average yield ratios range from 0.82 to 0.89, resulting in somewhat lower production levels. The average yield ratio for all 160 examples from developed countries is 0.92, close to Stanhill’s average relative yield of 0.91[23]. According to Model 2, the estimated organic food supply exceeds the current food supply in all food categories, with most estimates over 50% greater than the amount of food currently produced (Figure 1). The higher estimates in Model 2 result from the high average yield ratios of organic versus current methods of production in the developing world (Tables 1C and 3). The average yield ratio for the 133 examples from the developing world is 1.80. We consider Model 2 more realistic because it uses average yield ratios specific to each region of the world.

These two models likely bracket the best estimate of global organic food production. Model 1 may underestimate the potential yield ratios of organic to conventional production, since many agricultural soils in developed countries have been degraded by years of tillage, synthetic fertilizers, and pesticide residues. Conversion to organic methods on such soils typically results in an initial decrease

Table 4. Estimated nitrogen available for plant uptake from biological nitrogen fixation with leguminous cover crops, for the world and the US. For A, and F, data are from FAO Statistical Data Base[19] and USDA National Agriculture Statistics[35]; for B, data for the world are from Gallaway et al., 1995[36], and for the US from USDA-ERS[37] and the USDA National Agriculture Statistics[35]; for D, data are from sources listed in Appendix 2. Estimates are based on land area not currently in leguminous forage production.

		World	US
A	Area of total cropland	1513.2 million ha	177.3 million ha
B	Area in leguminous forage production	170.0 million ha	36.0 million ha
C	Area remaining for use in cover crops (A–B)	1362.1 million ha	141.3 million ha
D	Average N availability or fertilizer-equivalence from winter and off-season cover crops	102.8 kg N ha^{-1} yr^{-1} ($n = 77$, S.D. = 71.8)	95.1 kg N ha^{-1} yr^{-1} ($n = 32$, S.D. = 37.5)
E	Estimated N available from additional cover crops without displacing production (C × D)	140.0 million Mg N	13.4 million Mg N
F	Total synthetic N fertilizer in current use by conventional agriculture	82.0 million Mg N	10.9 million Mg N
G	Estimated N fixed by cover crops in excess of current synthetic fertilizer use (E–F)	58.0 million Mg N	2.5 million Mg N

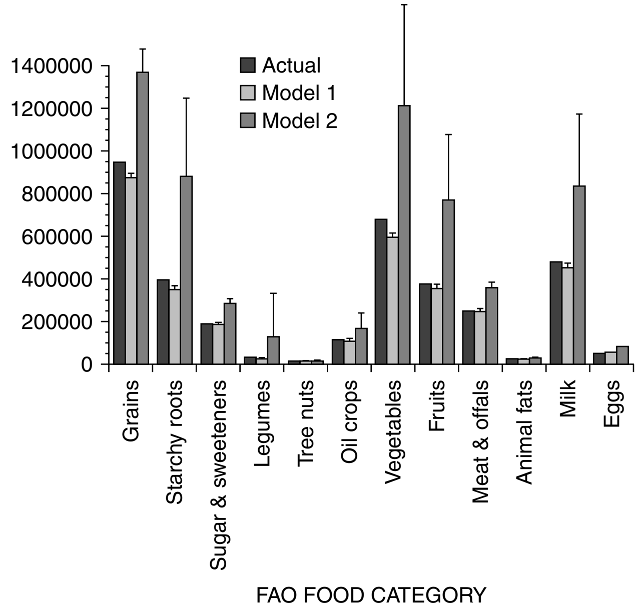

Figure 1. Estimates of the global food supply from two models of organic production compared with the actual food supply in 2001. Standard errors are given for food categories with multiple studies of yield ratios (see Table 1 and Appendix 1).

in yields, relative to conventional methods, followed by an increase in yields as soil quality is restored[7,25]. Model 2 may overestimate the yield ratios for the developing world to the extent that green-revolution methods are practiced.

Both models suggest that organic methods could sustain the current human population, in terms of daily caloric intake (Table 5). The current world food supply after losses[19] provides 2786 kcal person^{-1} day^{-1}. The average caloric requirement for a healthy adult[38] is between 2200 and 2500 kcal day^{-1}. Model 1 yielded 2641 kcal person^{-1} day^{-1}, which is above the recommended value, even if slightly less than the current availability of calories. Model 2 yielded 4381 kcal person^{-1} day^{-1}, which is 57% greater than current availability. This estimate suggests that organic production has the potential to support a substantially larger human population than currently exists. Significantly, both models have high yields of grains, which constitute the major caloric component of the human diet. Under Model 1, the grain yield is 93% that of current production. Under Model 2, the grain yield is 145% that of current production (Table 5).

The most unexpected aspect of this study is the consistently high yield ratios from the developing world (Table A1, Appendix 1). These high yields are obtained when farmers incorporate intensive agroecological techniques, such as crop rotation, cover cropping, agroforestry, addition of organic fertilizers, or more efficient water management[16,39]. In some instances, organic-intensive methods resulted in higher yields than conventional methods for the same crop in the same setting (e.g., the system of rice intensification (SRI) in ten developing countries[39]). Critics have argued that some of these examples exceed the intrinsic yield limits set by crop genetics and the environmental context[40]. (Such controversy surrounds the ‘SRI’ and our data include studies from both sides of this controversy.) Yet alternative agricultural methods may elicit a different pathway of gene expression than conventional methods do[41]. Thus, yield limits for conventionally grown crops may not predict the yield limits under alternative methods.

Crop rotation and yield-time adjustment

Organic grain production frequently uses a different rotation system than conventional production. For example, it is common in organic systems to have a three or four-year rotation (with legumes or other crops) for corn, while the conventional rotation often involves planting corn every other year. In situations like this, it is difficult to make yield comparisons between organic and conventional systems without some sort of time adjustment. Although the high variation among rotation systems worldwide makes it impossible to provide a general time–yield adjustment, evaluating potential differences in performance is important. A thorough evaluation of the rotation effect requires knowledge of the plot-to-plot yield differences between organic and conventional production and the rate of decline of both organic and conventional production as a function of the rotation sequence—information that has not yet been experimentally demonstrated. While rotations would undoubtedly differ under a global organic production system, we have no basis for concluding that this system would be unable to provide enough grain to feed the world.

Organic nitrogen fertilizer

In 2001, the global use of synthetic N fertilizers was 82 million Mg (metric ton)[19]. Our global estimate of N fixed by the use of additional leguminous crops as fertilizer is 140 million Mg, which is 58 million Mg greater than the amount of synthetic N currently in use (Table 4). Even in the US, where substantial amounts of synthetic N are used in agriculture, the estimate shows a surplus of available N through the additional use of leguminous cover crops between normal cropping periods. The global estimate is based on an average N availability or N-fertilizer equivalency of 102.8 kg N ha^{-1} (S.D. 71.8, $n = 76$, Table A2, Appendix 2). For temperate regions, the average is 95.1 kg N ha^{-1} (S.D. 36.9, $n = 33$) and for tropical regions, the average is 108.6 kg N ha^{-1} (S.D. 99.2, $n = 43$). These rates of biological N fixation and release can match N availability with crop uptake and achieve yields equivalent to those of high-yielding conventionally grown crops[42]. In temperate regions, winter cover crops grow well in fall after harvest and in early spring before planting of the main food crop[43]. Research at the Rodale Institute (Pennsylvania, USA) showed that red clover and hairy vetch as winter covers in an oat/wheat–corn–soybean rotation with no additional fertilizer inputs achieved yields comparable to those in conventional controls[24,25,44]. Even

Table 5. Caloric values for the actual food supply (2001, data from FAO[19]) and for the organic food supply estimated in Models 1 and 2 (Tables 2 and 3). For alcoholic beverages, seafood, and other aquatic products, no change in caloric intake was assumed.

Food category	**Actual food supply after losses**	**Actual per capita supply**	**Model 1 results**	**Ratio of model/ actual**	**Est. per capita supply, Model 1**	**Model 2 results**	**Ratio of model/ actual**	**Est. per capita supply, Model 2**
Units	**1000 Mg**	**Kcal day^{-1}**	**1000 Mg**		**Kcal day^{-1}**	**1000 Mg**		**Kcal day^{-1}**
Grain products	944,611	1335.3	876,599	0.93	1239.1	1,370,435	1.45	1937.2
Starchy roots	391,656	146.8	348,965	0.89	130.8	881,559	2.25	330.4
Sugars and sweeteners	187,040	247.7	187,975	1.01	249.0	283,565	1.52	375.6
Legumes (pulses)	32,400	53.8	26,438	0.82	43.9	124,099	3.83	205.9
Tree nuts	7,736	8.9	7,070	0.91	8.2	10,687	1.38	12.3
Oil crops and veg. oils	110,983	326.4	109,984	0.99	323.1	166,010	1.50	488.2
Vegetables	680,802	72.7	596,383	0.88	63.7	1,213,027	1.78	129.6
Fruits, excl. wine	372,291	77.8	355,538	0.96	74.3	771,443	2.07	161.2
Alcoholic beverages	199,843	64.0			64.0			64.0
Meat and offals	247,446	211.1	244,476	0.99	208.6	358,909	1.45	306.2
Animal fats	19,776	61.2	19,143	0.97	59.2	26,561	1.34	82.2
Milk, excl. butter	479,345	119.7	454,898	0.95	113.6	836,434	1.74	208.9
Eggs	50,340	32.3	53,360	1.06	34.2	78,323	1.56	50.2
Seafood	95,699	27.4			27.4			27.4
Other aquatic prod.	8,514	1.4			1.4			1.4
Total		2786.4			2640.7			4380.6

in arid and semi-arid tropical regions, where water is limiting between periods of crop production, drought-resistant green manures, such as pigeon peas or groundnuts, can be used to fix N[26,45,46]. Use of cover crops in arid regions has been shown to increase soil moisture retention[47], and management of dry season fallows commonly practiced in dry African savannas can be improved with the use of N-fixing cover crops for both N-fixation and weed control[48]. Areas in sub-Saharan Africa which currently use only very small amounts of N fertilizer (9 kg ha^{-1}, much of it on non-food crops[48]) could easily fix more N with the use of green manures, leading to an increase in N availability and yields in these areas[26]. In some agricultural systems, leguminous cover crops not only contribute to soil fertility but also delay leaf senescence and reduce the vulnerability of plants to disease[30].

Our estimates of N availability from leguminous cover crops do not include other practices for increasing biologically fixed N, such as intercropping[49], alley cropping with leguminous trees[50], rotation of livestock with annual crops[32], and inoculation of soil with free-living N-fixers[51]—practices that may add considerable N fertility to plant and animal production[52]. In addition, rotation of food-crop legumes, such as pulses, soy, or groundnuts, with grains can contribute as much as 75 kg N ha^{-1} to the grains that follow the legumes[33].

These methods can increase the N-use efficiency by plants. Since biologically available N is readily leached from soil or volatilized if not taken up quickly by plants, N use in agricultural systems can be as low as 50%[53]. Organic N sources occur in more stable forms in carbon-based compounds, which build soil organic matter and increase the amount of N held in the soil[25,54]. Consequently, the amount of N that must be added each year to maintain yields may actually decrease, because the release of organic N fixed in one season occurs over several years[30].

These results imply that, in principle, no additional land area is required to obtain enough biologically available N to replace the current use of synthetic N fertilizers. Although this scenario of biological N fixation is simple, it provides an assessment, based on available data, for one method of organic N-fertility production that is widely used by organic farmers and is fairly easy to implement on a large scale. This scenario is not intended to be prescriptive for any particular rotation or location, but to demonstrate the possibility of this type of cover-cropping system to fix large quantities of N without displacing food crops or expanding land area. The Farm Systems Trial at the Rodale Institute uses legume cover crops grown between main crops every third year as the only source of N fertility and reports comparable grain yields to those of conventionally managed systems, while using non-legume winter cover crops in other years to maintain soil quality and fertility and to suppress weeds (R. Seidel and P. Hepperly, personal communication, 2006). In practice, a range of methods acceptable in organic agriculture provides critical flexibility in N-management[32], including many sources other than cover crops. Although some environmental and economic circumstances pose challenges to reliance on leguminous fertilizers[55], the full potential of leguminous cover crops in agriculture is yet to be utilized. Implementation of existing knowledge could increase the use of green manures in many regions of the world[56]. Future selection for crop varieties and green manures that have higher rates of N fixation, especially in arid or semi-arid regions, and perform well under N-limiting conditions, as well as for improved strains of N-fixing symbionts, combined with reductions in the amount of N lost from legume-based production systems, and increases in the planting of legumes, hold great promise for increasing the role of biological N-fixation in fertility management[57]. The capacity for increased reliance on legume fertilizers would be even greater with substantive changes in the food system, such as reduction of food waste and feeding less grain to livestock[56].

Prospects for More Sustainable Food Production

Our results suggest that organic methods of food production can contribute substantially to feeding the current and future human population on the current agricultural land base, while maintaining soil fertility. In fact, the models suggest the possibility that the agricultural land base could eventually be reduced if organic production methods were employed, although additional intensification via conventional methods in the tropics would have the same effect. Our calculations probably underestimate actual output on many organic farms. Yield ratios were reported for individual crops, but many organic farmers use polycultures and multiple cropping systems, from which the total production per unit area is often substantially higher than for single crops[48,58]. Also, there is scope for increased production on organic farms, since most agricultural research of the past 50 years has focused on conventional methods. Arguably, comparable efforts focused on organic practices would lead to further improvements in yields as well as in soil fertility and pest management. Production per unit area is greater on small farms than on large farms in both developed and developing countries[59]; thus, an increase in the number of small farms would also enhance food production. Finally, organic production on average requires more hand labor than does conventional production, but the labor is often spread out more evenly over the growing season[25,60–62]. This requirement has the potential to alleviate rural unemployment in many areas and to reduce the trend of shantytown construction surrounding many large cities of the developing world.

The Millennium Ecosystem Assessment[17] recommends the promotion of agricultural methods that increase food production without harmful tradeoffs from excessive use of water, nutrients, or pesticides. Our models demonstrate that organic agriculture can contribute substantially to a more sustainable system of food production. They suggest not only that organic agriculture, properly intensified, could produce much of the world's food, but also that developing countries could increase their food security with organic agriculture. The results are not, however, intended as forecasts of instantaneous local or global production after conversion to organic methods. Neither do we claim that yields by organic methods are routinely higher than yields from green-revolution methods. Rather, the results show the potential for serious alternatives to green-revolution agriculture as the dominant mode of food production.

In spite of our optimistic prognosis for organic agriculture, we recognize that the transition to and practice of organic agriculture contain numerous challenges—agronomically, economically, and educationally. The practice of organic agriculture on a large scale requires support from research institutions dedicated to agro-ecological methods of fertility and pest management, a strong extension system, and a committed public. But it is time to put to rest the debate about whether or not organic agriculture can make a substantial contribution to the food supply. It can, both locally and globally. The debate should shift to how to allocate more resources for research on agroecological methods of food production and how to enhance the incentives for farmers and consumers to engage in a more sustainable production system. Finally, production methods are but one component of a sustainable food system. The economic viability of farming methods, land tenure for farmers, accessibility of markets, availability of water, trends in food consumption, and alleviation of poverty are essential to the assessment and promotion of a sustainable food system.

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Appendix 1: Yield Ratios

The studies used to estimate the yield ratios for different food categories in Table 1 come from 91 sources in Table A1 describing results from experiments at research stations, comparisons of paired farms, and comparisons before and after the transition to organic production. The data come from 53 countries and 12 US states. Some comparisons during the transition to organic production come from surveys, especially in the data for the developing world. Data range in observation length from one growing season to over 20 years. Despite the observation that yields following conversion from conventional to organic production initially decline and then tend to increase over time[24], we did not omit studies of short duration so as not to bias estimates of relative yield. We included data from previous comparisons of organic and conventional production, notably Stanhill[23], Lampkin and Padel[63], and McDonald et al.[64] for the SRI in the developing world. Over 80% of the examples listed come directly from peer-reviewed journal articles or are cited or figured in them. The remainder come from technical books, conference proceedings, technical reports from universities, government agencies or independent research foundations, or the Web site of a university research station.

For the developing world, there are fewer controlled comparisons of organic versus non-organic methods than for the developed world. Much of our data in Table A1B comes from one source (Pretty and Hine[65]), which is a compilation from surveys in developing countries of yield comparisons before and after farmers adopted specific agroecological practices. In order to determine whether the survey data biased our results, we tested the hypothesis that the average yield ratio based on survey data and unreported methods differed significantly from the average yield ratio based on experimental data and quantitative comparisons of paired farms. The only food category with a substantial sample size of yield ratios in both categories of studies was grains ($n = 102$). We subdivided grains into rice and all other grains, because more than half of our data concern rice but these data are quite unequally distributed between the two categories of studies. For rice ($n = 61$), a t-test ($p = 0.55$) comparing the average yield ratios from surveys and unreported methods versus experiments and paired farms failed to reject the null hypothesis that the average yield ratios do not differ significantly. For all other grains ($n = 41$), a t-test ($p = 0.45$) also failed to reject the null hypothesis. Thus, we concluded that the survey data have not unduly biased our results for the developing world. (No data for the developed world come from surveys.)

Table A1. Yield ratios of organic production : non-organic production, grouped by FAO food categories analyzed in the text. (A) Data from developed countries, where comparisons are between organic and conventional (green-revolution) production methods. (B) Data from developing countries, where comparisons are primarily between organic and non-intensive methods.

(A) Developed countries

Crop	Yield ratio	Location	Reference
Grains			
Barley, summer	1.03	Germany	Keopf, H.H., Pettersson, B.D., and Schaumann, W. 1976. Biodynamic Agriculture. The Anthroposophic Press, Spring Valley, NY.
Barley, winter	1.14	Germany	Keopf, H.H. et al. 1976. Op. cit.
Barley	0.68	New Zealand	Nguyen, M.L. and Haynes, R.J. 1995. Energy and labour efficiency for three pairs of conventional and alternative mixed cropping (pasture-arable) farms in Canterbury, New Zealand. Agriculture, Ecosystems, and Environment 52:163–172.
Barley	0.78	Sweden	Dlouhy, J. 1981. Alternative forms of agriculture—quality of plant products from conventional and biodynamic growing. Report 91, Department of Plant Husbandry, Swedish University of Agricultural Sciences, Uppsala.
Barley	0.65	Sweden	Dlouhy, J. 1981. Op. cit.
Barley	0.75	Switzerland	Eidg. Forschungsanstalt für Betriebswirtschaft und Landtechnik. 1993. Bericht über biologisch bewirtschaftete Betriebe 1991. Tänikon, Switzerland.
Barley	0.86	Switzerland	Steinmann, R. 1983. Biological Agriculture—A Bookkeeping Comparison. Report No. 19, Swiss Federal Research Station for Farm Management and Agricultural Engineering, Tänikon, Switzerland.
Corn, sweet	0.82	Canada, Nova Scotia	Warman, P.R. and Havard, K.A. 1998. Yield, vitamin and mineral contents of organically and conventionally grown potatoes and sweet corn. Agriculture, Ecosystems and Environment 68:207–216.
Corn	1.16	Canada, Ontario	Stonehouse, P. 1991. Economics of Weed Control in Alternative Farming Systems. In Proceedings of the 5th REAP Conference. McGill University, Macdonald Campus, Quebec.

Table A1. Continued.

Crop	Yield ratio	Location	Reference
Corn, sweet	0.60	Canada, Ontario	Sellen, D., Tolman, J.H., McLeod, D., Weersink, A., and Yiridoe, E. 1993. Economics of Organic and Conventional Horticulture Production. Working Paper, Department of Agricultural Economics and Business, University of Guelph, Guelph, Ontario.
Corn	0.89	Switzerland	Steinmann, R. 1983. Op. cit.
Corn	0.94	US, 7 states	Liebhardt, B. 2001. Get the facts straight: organic agriculture yields are good. Organic Farming Research Foundation Information Bulletin 10, 1–5. Santa Cruz, CA. Available at Web site: http://www.ofrf.org/publications/news/IB10.pdf
Corn	0.95	US, California	Clark, M.S., Ferris, H., Klonsky, K., Lanini, W.T., van Bruggen, A.H.C., and Zalom, F.G. 1998. Agronomic, economic, and environmental comparison of pest management in conventional and alternative tomato and corn systems in northern California. Agriculture, Ecosystems and Environment 68:51–71.
Corn	1.01	US, California	Poudel, D.D., Horwath, W.R., Lanini, W.T., Temple, S.R., and van Bruggen, A.H.C. 2002. Comparison of soil N availability and leaching potential, crop yields and weeds in organic, low-input and conventional farming systems in northern California. Agriculture, Ecosystems and Environment 90:125–137.
Corn	0.92	US, Iowa	Delate, K. and Cambardella, C.A. 2004. Agroecosystem performance during transition to certified organic grain production. Agronomy Journal 96:1288–1298.
Corn	0.92	US, midwest	Lockeretz, W., Shearer, G., and Kohl, D.H. 1981. Organic farming in the corn belt. Science 211:540–547.
Corn	0.91	US, Minnesota	Porter, P., Huggins, D., Perillo, C., Quiring, S., and Crookston, R. 2003. Organic and other management strategies with two- and four-year crop rotations in Minnesota. Agronomy Journal 95:233–244.
Corn	0.92	US, Nebraska	Sahs, W.W., Lesoing, G.W., and Francis, C.A. 1992. Rotation and manure effects on crop yields and soil characteristics in eastern Nebraska. Agronomy Abstracts 84:155.
Corn	0.93	US, New Jersey	Brumfield, R.G., Rimal, A., and Reiners, S. 2000. Comparative cost analyses of conventional, integrated crop management, and organic methods. HortTechnology 10:785–793.
Corn	1.30	US, Ohio	National Research Council. 1989. Alternative Agriculture. National Academy Press, Washington, DC.
Corn	1.17	US, Pennsylvania	National Research Council. 1989. Op. cit.
Corn	0.86	US, Pennsylvania	Pimentel, D., Hepperly, P., Hanson, J., Douds, D., and Seidel, R. 2005. Environmental, energetic, and economic comparisons of organic and conventional farming systems. Bioscience 55:573–582.
Corn	0.89	US, Pennsylvania	Pimentel, D. et al. 2005. Op. cit.
Corn	0.84	US, South Dakota	Smolik, J.D., Dobbs, T.L., and Rickerl, D.H. 1995. The relative sustainability of alternative, conventional, and reduced-till farming systems. American Journal of Alternative Agriculture 10:25–35.
Corn	0.95	US, South Dakota	Dobbs, T. and Smolik, J.D. 1996. Productivity and profitability of conventional and alternative farming systems: A long-term on-farm paired comparison. Journal of Sustainable Agriculture 9:63–77.
Corn	1.04	US, western corn belt	Roberts, K.J., Warnken, F., and Schneeberger, K.C. 1979. The economics of organic crop production in the Western corn belt. Agricultural Economics Paper No. 1979-6. Department of Agricultural Economics, University of Missouri, Columbia, MO. p. 63–101.
Grains	1.24	Germany	Keopf, H.H. 1981. The principles and practice of biodynamic agriculture. In B. Stonehouse (ed.). Biological Husbandry. Butterworths, London. p. 237–250.
Oats	1.21	Germany	Koepf, H.H. et al. 1976, Op. cit.
Oats	0.85	Switzerland	Steinmann, R. 1983, Op. cit.
Oats	1.00	US, midwest	Lockeretz, W. et al. 1981. Op. cit.
Oats	1.23	US, Ohio	National Research Council. 1989. Op. cit.
Oats	0.73	US, western corn belt	Roberts, K.J. et al. 1979. Op. cit.
Oats	0.85	UK	Trewavas, A. 2004. A critical assessment of organic farming-and-food assertions with particular respect to the UK and the potential environmental benefits of no-till agriculture. Crop Protection 23:757–781.

Table A1. Continued.

Crop	Yield ratio	Location	Reference
Rice	0.85	Spain	Scialabba, N. El-H. and Hattam, C. (eds). 2002. Organic Agriculture, Environment, and Food Security. FAO, Rome.
Rye	1.26	Germany	Koepf, H.H. et al. 1976. Op. cit.
Rye	0.94	Germany	Raupp, J. 1996. Quality investigations with products of the long-term fertilization trial in Darmstadt. In J. Raupp (ed.). Quality of Plant Products Grown with Manure Fertilization. Vol. 9. Institute for Biodynamic Research, Darmstadt. p. 13–33.
Rye	0.96	Germany	Raupp, J. 1996. Op. cit.
Rye	0.75	Germany	Raupp, J. 1996. Op. cit.
Rye	0.78	Germany	Raupp, J. 1996. Op. cit.
Rye	0.81	Switzerland	Eidg. Forschungsanstalt für Betriebswirtschaft und Landtechnik. 1993. Op. cit.
Wheat	0.96	Australia	Wynen, E. 1994. Economics of organic farming in Australia. In N.H. Lampkin and S. Padel (eds). The Economics of Organic Farming: An International Perspective, CAB International, Wallingford, UK. p. 185–199.
Wheat	1.45	Australia	Leu, A. 2004. Organic agriculture can feed the world. Acres USA. January 2004.
Wheat, winter	1.14	Canada, Ontario	Stonehouse, P. 1991. Op. cit.
Wheat	1.12	Germany	Koepf, H.H. et al. 1976. Op. cit.
Wheat, spring	1.01	Germany	Raupp, J. 1996. Op. cit.
Wheat, spring	1.02	Germany	Raupp, J. 1996. Op. cit.
Wheat, Oats, Rye	1.00	Germany	Dabbert, S. 1990. Zur Optimalen Organisation Alternativer Landwirtschaftlicher Betriebe. Agrarwirtschaft Sonderheft 124. Verlag Alfred Strothe, Frankfurt.
Wheat	1.09	Israel	Levi, M. 1979. Principle of bio-organic agriculture. The Biosphere 8:30–35.
Wheat	0.68	New Zealand	Nguyen, M.L. and Haynes, R.J. 1995. Op. cit.
Wheat	0.88	Sweden, Jarna	Granstedt, A.G. and Kjellenberg, L. 1996. Quality investigations with the K-trial, Jarna, and other Scandinavian fertilization experiments. In J. Raupp (ed.). Quality of Plant Products Grown with Manure Fertilization. Vol. 9. Institute for Biodynamic Research. Darmstadt. p. 3–12.
Wheat	0.80	Sweden, Uppsala	Granstedt, A.G. and Kjellenberg, L. 1996. Op. cit.
Wheat	0.77	Switzerland	Eidg. Forschungsanstalt für Betriebswirtschaft und Landtechnik. 1993. Op. cit.
Wheat	0.86	Switzerland	Steinmann, R. 1983. Op. cit.
Wheat	0.87	Switzerland	Mäder, P., Fleißbach, A., Dubois, D., Gunst, L., Fried, P. and Niggli, U. 2002. Soil fertility and biodiversity in organic farming. Science 296:1694–1697.
Wheat	0.98	US, California	McGuire, A.M., Bryant, D.C., and Denison, R.F. 1998. Wheat yields, nitrogen uptake, and soil moisture following winter legume cover crop vs. fallow. Agronomy Journal 90:404–410.
Wheat	0.96	US, California	McGuire, A.M. et al. 1998. Op. cit.
Wheat	0.83	US, California	McGuire, A.M. et al. 1998. Op. cit.
Wheat	0.81	US, California	McGuire, A.M. et al. 1998. Op. cit.
Wheat	0.56	US, Michigan	Kellogg Biological Station Long Term Ecological Research, http://lter.kbs.msu.edu.
Wheat	0.55	US, Michigan	Kellogg Biological Station Long Term Ecological Research, http://lter.kbs.msu.edu.
Wheat	0.57	US, midwest	Lockeretz, W. et al. 1981. Op. cit.
Wheat	0.78	US, New York, Pennsylvania	Berardi, G.M. 1978. Organic and conventional wheat production: Examination of energy and economics. Agro-Ecosystems 4:367–376.
Wheat	1.05	US, Ohio	National Research Council. 1989. Op. cit.
Wheat	1.00	US, Pennsylvania	National Research Council. 1989. Op. cit.
Wheat	1.09	US, South Dakota	Smolik, J.D. et al. 1995. Op. cit.
Wheat	0.97	US, South Dakota, Michigan	Liebhardt, B. 2001. Op. cit.
Wheat	1.00	US, western corn belt	Roberts, K.J. et al. 1979. Op. cit.
Wheat	1.15	UK	Jenkinson, D.S., Bradbury, N.J., and Coleman, K. 1994. In R.A. Leigh and A.E. Johnston (eds). Long-term Experiments in Agricultural and Ecological Sciences. CAB International, Wallingford, UK. p. 117–138.
Wheat	0.68	UK	Trewavas, A. 2004. Op. cit.
Starchy roots			
Potatoes	0.85	Canada, Nova Scotia	Warman, P.R. and Havard, K.A. 1998. Op. cit.

Table A1. Continued.

Crop	Yield ratio	Location	Reference
Potatoes	1.18	Germany	Koepf, H.H. et al. 1976. Op. cit.
Potatoes	0.90	Germany	Raupp, J. 1996. Op. cit.
Potatoes	0.96	Germany	Raupp, J. 1996. Op. cit.
Potatoes	0.96	Germany	Raupp, J. 1996. Op. cit.
Potatoes	1.06	Germany	Raupp, J. 1996. Op. cit.
Potatoes	1.00	Israel	Levi, M. 1979. Op. cit.
Potatoes	0.86	Sweden	Dlouhy, J. 1981. Op. cit.
Potatoes	0.69	Sweden	Dlouhy, J. 1981. Op. cit.
Potatoes	0.82	Sweden, Jarna	Granstedt, A.G. and Kjellenberg, L. 1996. Op. cit.
Potatoes	0.81	Sweden, Uppsala	Granstedt, A.G. and Kjellenberg, L. 1996. Op. cit.
Potatoes	0.62	Switzerland	Mäder, P. et al. 2002. Op. cit.
Potatoes	0.74	Switzerland	Eidg. Forschungsanstalt für Betriebswirtschaft und Landtechnik. 1993. Op. cit.
Potatoes	1.03	Switzerland	Steinmann, R. 1983. Op. cit.
Sugars and sweeteners			
Sugar beet	1.02	Germany	Koepf, H.H. et al. 1976. Op. cit.
Sugar beet	0.99	Israel	Levi, M. 1979. Op. cit.
Legumes (Pulses)			
Beans, bush	0.83	Germany	Lindner, U. 1987. Alternativer Anbau–eine Alternative für den Erwerbsgemüsebau Gartenbauliche Versuchsberichte der Landwirtschaftkammer Rheinland 5:106–109.
Beans, dry	1.17	US, Maine	Eggert, F.M. 1983. Effect of soil management practices on yield and foliar nutrient concentration of dry beans, carrots and tomatoes. In W. Lockeretz (ed.). Environmentally Sound Agriculture. Praeger, New York. p. 247–259.
Beans, green	0.90	Canada, Ontario	Sellen, D. et al. 1993. Op. cit.
Beans, runner	0.65	Germany	Lindner, U. 1987. Op. cit.
Beans, winter	0.72	UK	Trewavas, A. 2004. Op. cit.
Peas	0.83	New Zealand	Nguyen, M.L. and Haynes, R.J. 1995. Op. cit.
Peas, dried	0.61	UK	Trewavas, A. 2004. Op. cit.
Oil crops			
Soybeans	0.94	US, 5 states	Liebhardt, B. 2001. Op. cit.
Soybeans	1.01	US, Iowa	Delate, K. and Cambardella, C.A. 2004. Op. cit.
Soybeans	0.95	US, midwest	Lockeretz, W. et al. 1981. Op. cit.
Soybeans	0.81	US, Minnesota	Porter, P. et al. 2003. Op. cit.
Soybeans	1.39	US, Ohio	National Research Council. 1989. Op. cit.
Soybeans	1.00	US, Pennsylvania	Hanson, J.C., Lichtenberg, E., and Peters, S.E. 1997. Organic versus conventional grain production in the mid-Atlantic: an economic and farming system overview. American Journal of Alternative Agriculture 12:2–9.
Soybeans	1.26	US, Pennsylvania	National Research Council. 1989. Op. cit.
Soybeans	0.97	US, Pennsylvania	Pimentel, D. et al. 2005. Op. cit.
Soybeans	0.88	US, Pennsylvania	Pimentel, D. et al. 2005. Op. cit.
Soybeans	1.00	US, South Dakota	Smolik, J.D. et al. 1995. Op. cit.
Soybeans	1.03	US, South Dakota	Smolik, J.D. et al. 1995. Op. cit.
Soybeans	0.77	US, South Dakota	Dobbs, T. and Smolik, J.D. 1996. Op. cit.
Soybeans	0.87	US, western corn belt	Roberts, K.J. et al. 1979. Op. cit.
Vegetables			
Beetroot	1.01	Germany	Raupp, J. 1996. Op. cit.
Beetroot	1.06	Germany	Raupp, J. 1996. Op. cit.
Beetroot	0.91	Germany	Lindner, U. 1987. Op. cit.
Cabbage	0.98	Canada, Nova Scotia	Warman, P.R. and Havard, K.A. 1997. Op. cit.
Cabbage	0.81	Canada, Ontario	Sellen, D. et al. 1993. Op. cit.
Cabbage	0.67	Germany	Lindner, U. 1987. Op. cit.
Carrots	1.06	Canada, Nova Scotia	Warman, P.R. and Havard, K.A. 1997. Yield, vitamin and mineral contents of organically and conventionally grown carrots and cabbage. Agriculture, Ecosystems and Environment 61:155–162.

Table A1. Continued.

Crop	Yield ratio	Location	Reference
Carrots	1.04	Germany	Raupp, J. 1996. Op. cit.
Carrots	1.08	Germany	Raupp, J. 1996. Op. cit.
Carrots	0.97	Israel	Levi, M. 1979. Op. cit.
Carrots	0.95	US, Maine	Eggert, F.M. 1983. Op. cit.
Cauliflower	0.64	Germany	Lindner, U. 1987. Op. cit.
Celeriac	0.96	Germany	Lindner, U. 1987. Op. cit.
Endive	0.80	Germany	Lindner, U. 1987. Op. cit.
Fennel	0.76	Germany	Lindner, U. 1987. Op. cit.
Kohlrabi	0.84	Germany	Lindner, U. 1987. Op. cit.
Leeks	0.92	Germany	Lindner, U. 1987. Op. cit.
Lettuce	0.76	Germany	Lindner, U. 1987. Op. cit.
Onions, Spanish	0.78	Canada, Ontario	Sellen, D. et al. 1993. Op. cit.
Savoy	0.83	Germany	Lindner, U. 1987. Op. cit.
Spinach	0.65	Germany	Lindner, U. 1987. Op. cit.
Tomatoes	0.55	Canada, Ontario	Sellen, D. et al. 1993. Op. cit.
Tomatoes	1.00	US, California	Liebhardt, B. 2001. Op. cit.
Tomatoes	0.83	US, California	Clark, M.S. et al. 1998. Op. cit.
Tomatoes	0.89	US, California	Clark, M.S. et al. 1998. Op. cit.
Tomatoes	0.97	US, California	Poudel, D.D. et al. 2002. Op. cit.
Tomatoes	1.00	US, California	Drinkwater, L.E. et al. 1995. Op. cit.
Tomatoes	1.04	US, Maine	Eggert, F.M. 1983. Op. cit.
Vegetables	0.68	Canada	Parsons, W. 2002. Organic fruit and vegetable production: Is it for you? Vista: Statistics Canada; Agriculture Division.
Vegetables	0.71	UK	Department for Environment, Food, and Rural Affairs (DEFRA). 2002. www.hdra.org.uk/pdfs/Conversion_report_2001-2002.pdf.
Vegetables, leafy	1.00	Japan	Xu, H.L., Wang, R., Xu, R.Y., Mridha, M.A.U., and Goyal, S. 2003. Yield and quality of leafy vegetables grown with organic fertilizations. Acta Horticulturae 627:25–33.
Fruits			
Apples	1.00	US, Washington	Reganold, J.P., Glover, J.D., Andrews, P.K., and Hinman, J.R. 2001. Sustainability of three apple production systems. Nature 410:926–930.
Fruits	0.91	Canada	Parsons, W. 2002. Op. cit.
Meat and offals			
Beef, bull	1.01	Germany	Lölau, S. and Zerger, U. 1989, 1991. Datenauswertung im Rahmen des Agrarkulturpreises der KLS-Stiftung. Munich (cited in Lampkin, N.H. and Padel, S. (eds). 1994. Op. cit.)
Beef, milk cows	1.07	Germany	Koepf, H.H. et al. 1976. Op. cit.
Beef	1.01	UK	Younie, D., Watson, C., Halliday, G., Armstrong, G., Slee, W., and Daw, M. 1990. Organic Beef in Practice. Scottish Agricultural College, Aberdeen.
Chicken, broiler	0.86	Italy	Castellini, C., Mugnai, C., and Dal Bosco, M. 2002. Effect of organic production system on broiler carcass and meat quality. Meat Science 60:219–225.
Lamb	0.86	Italy	Morbidini, L., Sarti, D.M., Pollidori, P., and Valigi, A. 1999. Carcass, meat and fat quality in Italian Merino derived lambs obtained with 'organic' farming systems. FAO-CIHEAM Network. http://ressources.ciheam.org/om/pdf/a46/01600108.pdf
Pork	1.11	Germany	Lölau, S. and Zerger, U. 1989, 1991. Op. cit.
Pork	0.98	Germany	Sundrum, A., Bütfering, L., Henning, M., and Hoppenbrock, K.H. 2000. Effects of on-farm diets for organic pig production on performance and carcass quality. Journal of Animal Science 78:1199–1205.
Pork	1.00	Sweden	Olsson, V., Andersson, K., Hansson, I., and Lundström, K. 2003. Differences in meat quality between organically and conventionally produced pigs. Meat Science 64:287–297.
Milk, excl. butter			
Milk	1.06	Australia	Dornom, H. and Tribe, D.E. 1976. Energetics of dairying in Gippsland. Search 7:431–433.

Table A1. Continued.

Crop	Yield ratio	Location	Reference
Milk	0.80	Canada, Quebec	Burgoyne, D. 1992. Analyse économique comparée de l'impact du niveau d'intensification, de l'utilisation d'intrants et de la production biologique sur la rentabilité des enterprises laitières au Québec. MSc thesis, FSAA, Université Laval, Quebec.
Milk	0.98	Denmark	Kristensen, T. and Kristensen, E.S. 1998. Analysis and simulation modelling of the production in Danish organic and conventional dairy herds. Livestock Production Science 54:55–65.
Milk	0.95	Denmark	Refsgaard, K., Halberg, N., and Kristensen, E.S. 1998. Energy utilization in crop and dairy production in organic and conventional livestock production systems. Agricultural Systems 57:599–630.
Milk	0.90	Germany	Winter, R. 1991. Economic questions of dairy production in ecological agriculture in northern Germany. In E. Boehncke and V. Molkenthin (eds). Alternatives in Animal Husbandry. Proceedings of the International Conference, July 1991. University of Kassel, Witzenhausen, Germany.
Milk	0.78	Germany	Haas, G., Wetterich, F., and Köpke, U. 2001. Comparing intensive, extensified and organic grassland farming in southern Germany by process life cycle assessment. Agriculture, Ecosystems and Environment 83:43–53.
Milk	1.29	Germany	Koepf, H.H. 1981. Op. cit.
Milk	0.78	Norway	Reksen, O., Tverdal, A., and Ropstad, E. 1999. A comparative study of reproductive performance in organic and conventional dairy husbandry. Journal of Dairy Science 82:2605–2610.
Milk	0.91	Sweden	Cederberg, C. and Mattsson, B. 2000. Life cycle assessment of milk production—a comparison of conventional and organic farming. Journal of Cleaner Production 8:49–60.
Milk	0.99	Switzerland	Eidg. Forschungsanstalt für Betriebswirtschaft und Landtechnik. 1993. Op. cit.
Milk	1.00	UK	Haggar, R. and Padel, S. 1996. Conversion to Organic Milk Production, Institute of Grassland and Environmental Research (IGER) Technical Review no. 4, Aberystwyth, UK.
Milk	0.91	UK	Houghton, M. and Poole, A.H. 1990. Organic Milk Production. Genus Information Unit Report 70. Genus Management, Wrexham, UK.
Milk	0.99	UK	Padel, S. 2000. Strategies of organic milk production. In M. Hovi and M. Bouilhol (eds). Human-animal Relationship: Stockmanship and Housing in Organic Livestock Systems, Proceedings of the 3rd NAHWOA (Network for Animal Health and Welfare in Organic Agriculture) Workshop. p. 121–135. Available at Web site: http://www.veeru.reading.ac.uk/organic/ProceedingsFINAL.pdf
Eggs			
Eggs	1.06	Germany	Lölau, S. and Zerger, U. 1989, 1991. Op. cit.

(B) Developing countries

Crop	Yield ratio	Location	Reference
Grains			
Barley	1.43	Peru	Altieri, M. 1999. Applying agroecology to enhance the productivity of peasant farming systems in Latin America. Environment, Development and Sustainability 1:197–217.
Maize	1.37	Argentina	Pretty, J. and Hine, R. 2001. Reducing food poverty with sustainable agriculture: a summary of new evidence. Centre for Environment and Society, Essex University. Available at Web site: http://www2.essex.ac.uk/ces/ResearchProgrammes/CESOccasionalPapers/SAFErepSUBHEADS.htm
Maize	1.30	Benin	Pretty, J. and Hine, R. 2001. Op. cit.
Maize	1.31	Brazil	Pretty, J. and Hine, R. 2001. Op. cit.
Maize	1.20	Brazil	Altieri, M. 2001. Applying agroecology to enhance the productivity of peasant farming systems in Latin America. Paper presented to Conference, Reducing Poverty through Sustainability, Saint James Palace, London.
Maize	3.50	Brazil	Altieri, M. 2001. Op. cit.

Table A1. Continued.

Crop	Yield ratio	Location	Reference
Maize	2.78	China	Pretty, J. and Hine, R. 2001. Op. cit.
Maize	1.38	China	Pretty, J. and Hine, R. 2001. Op. cit.
Maize	1.09	China	Pretty, J. and Hine, R. 2001. Op. cit.
Maize	1.71	Colombia	Pretty, J. and Hine, R. 2001. Op. cit.
Maize	3.71	Guatemala	Pretty, J. and Hine, R. 2001. Op. cit.
Maize	3.00	Honduras	Pretty, J. and Hine, R. 2001. Op. cit.
Maize	2.28	Honduras	Pretty, J. and Hine, R. 2001. Op. cit.
Maize	2.00	Kenya	Pretty, J. and Hine, R. 2001. Op. cit.
Maize	3.49	Kenya	Pretty, J. and Hine, R. 2001. Op. cit.
Maize	1.46	Kenya	Pretty, J. and Hine, R. 2001. Op. cit.
Maize	1.50	Malawi	Pretty, J. and Hine, R. 2001. Op. cit.
Maize	1.33	Nepal	Pretty, J. and Hine, R. 2001. Op. cit.
Maize	3.14	Nicaragua	Pretty, J. and Hine, R. 2001. Op. cit.
Maize	1.71	Niger	Pretty, J. and Hine, R. 2001. Op. cit.
Maize	2.22	Paraguay	Pretty, J. and Hine, R. 2001. Op. cit.
Maize	1.65	Peru	Altieri, M. 1999. Op. cit.
Maize	2.50	Peru	Altieri, M. 2001. Op. cit.
Maize	1.20	Philippines	Pretty, J. and Hine, R. 2001. Op. cit.
Maize	3.27	Philippines	Pretty, J. and Hine, R. 2001. Op. cit.
Maize	1.26	Sri Lanka	Scialabba, N. El-H. and Hattam, C. (eds). 2003. Op cit..
Maize	2.00	Tanzania	Pretty, J. and Hine, R. 2001. Op. cit.
Millet	1.73	Ethiopia	Pretty, J. and Hine, R. 2001. Op. cit.
Rice	1.08	Bangladesh	Pretty, J. and Hine, R. 2001. Op. cit.
Rice	1.12	China	Pretty, J. and Hine, R. 2001. Op. cit.
Rice	1.08	Indonesia	Pretty, J. and Hine, R. 2001. Op. cit.
Rice	1.00	Sri Lanka	Pretty, J. and Hine, R. 2001. Op. cit.
Rice	1.28	Sri Lanka	Pretty, J. and Hine, R. 2001. Op. cit.
Rice	1.09	Vietnam	Pretty, J. and Hine, R. 2001. Op. cit.
Rice, SRI	0.93	Bangladesh	Latif, M.A., Islam, M.R., Ali, M.Y., and Saleque, M.A. 2005. Validation of the system of rice intensification (SRI) in Bangladesh. Field Crops Research 93:281–292.
Rice, SRI	0.84	Bangladesh	Latif, M.A. et al. 2005. Op. cit.
Rice, SRI	1.17	Bangladesh	Latif, M.A. et al. 2005. Op. cit.
Rice, SRI	0.89	Bangladesh	Latif, M.A. et al. 2005. Op. cit.
Rice, SRI	1.18	Bangladesh	Latif, M.A. et al. 2005. Op. cit.
Rice, SRI	1.29	Madagascar	Barison, J. 2002. Evaluation of nutrient uptake and nutrient-use efficiency of SRI and conventional rice cultivation methods in Madagascar. In N. Uphoff, E.C.F. Fernandes, L.P. Yuan, J. Peng, S. Rafaralahy, and J. Rabenandrasana (eds). Assessments of the System of Rice Intensification (SRI): Proceedings of an International Conference, Sanya, China, CIIFAD, Ithaca, NY. p. 143–147.
Rice, SRI	1.20	Bangladesh	BRRI (http://ciifad.cornell.edu/sri/countries/bangladesh/bangrisrifnl.pdf), cited in McDonald, A.J., Hobbs, P.R., and Riha, S.J. 2005. Does the system of rice intensification outperform conventional best management? A synopsis of the empirical record. Field Crops Research 96:31–36.
Rice, SRI	1.22	China	Shengfu, A., Xiehui, W., Zhongjiong, X., Shixiu, X., Chengquan, L., and Yangchang, L. 2002. Assessment of using SRI with the super hybrid rice variety Liangyoupei 9. In N. Uphoff et al. (eds). Op. cit. p. 112–115.
Rice, SRI	1.19	India	MSSRF (http://ciifad.cornell.edu/sri/countries/india/), cited in McDonald, A.J. et al. 2005. Op. cit.
Rice, SRI	1.11	Laos	Welthungerhilfe (http://ciifad.cornell.edu/sri/countries/laos/laoritr102.pdf), cited in McDonald, A.J. et al. 2005. Op. cit.
Rice, SRI	1.10	Sri Lanka	Nissanka, S. and Bandara, T. 2004. Comparison of productivity of system of rice intensification and conventional rice farming systems in the dry-zone region of Sri Lanka. Fourth International Crop Science Congress (ICSC2004). Available at Web site: http://www.cropscience.org.au/icsc2004/poster/1/2/1177_nissankara.htm
Rice, SRI	1.09	China	Sheehy, J.E., Peng, S., Dobermann, A., Mitchell, P.L., Ferrer, A., Jianchang, Y., Zou, Y., Zhong, X., and Huang, J. 2004. Fantastic yields in the system of rice intensification: fact or fallacy? Field Crops Research 88:1–8.

Table A1. Continued.

Crop	Yield ratio	Location	Reference
Rice, SRI	1.09	Indonesia	Markarim, A.K., Balasubramanian, V., Zaini, Z., Syamsiah, I., Diratmadja, I.G.P.A., Arafah, H., Wardana, I.P., and Gani, A. 2002. System of rice intensification (SRI): Evaluation of seedling age and selected components. In B.A. Bouman, H. Hengsdijk, B. Hardy, P.S. Bindraban, T.P. Tuong, and J.K. Ladha (eds). Water-wise Rice Production, Proceedings of International Workshop on Water-Wise Rice Production, International Rice Research Institute. Los Banos, Phillipines, p. 356.
Rice, SRI	1.02	China	Qingquan, Y. 2002. The system of rice intensification and its use with hybrid rice varieties in China. In N. Uphoff et al. (eds). Op. cit. p. 109–111.
Rice, SRI	1.02	China	Shao-hua, W., Weixing, C., Dong, J., Tingbo, D., and Yan, Z. 2002. Physiological characteristics and high-yield techniques with SRI rice. In N. Uphoff et al. (eds). Op. cit. p. 116–124.
Rice, SRI	1.02	China	Shao-hua, W. et al. 2002. Op. cit.
Rice, SRI	1.02	Bangladesh	Duxbury, J.M., cited in McDonald, A.J. et al. 2005. Op. cit.
Rice, SRI	0.99	China	Sheehy, J.E. et al. 2004. Op. cit.
Rice, SRI	0.95	Nepal	Evans, C., Justice, S., and Shrestha, S. 2002. Experience with the system of rice intensification in Nepal. In N. Uphoff et al. (eds). Op. cit. p. 64–66.
Rice, SRI	0.95	China	Shao-hua, W. et al. 2002. Op. cit.
Rice, SRI	0.94	China	Shao-hua, W. et al. 2002. Op. cit.
Rice, SRI	0.93	China	Shao-hua, W. et al. 2002. Op. cit.
Rice, SRI	0.92	Bangladesh	Duxbury, J.M., cited in McDonald, A.J. et al. 2005. Op. cit.
Rice, SRI	0.91	China	Sheehy, J.E. et al. 2004. Op. cit.
Rice, SRI	0.90	Thailand	Gypmantasiri, P. 2002. Experience with the system of rice intensification in northern Thailand. In N. Uphoff et al. (eds). Op. cit. p. 75–79.
Rice, SRI	0.86	Laos	DED (http://ciifad.cornell.edu/sri/countries/laos/laoritr102.pdf)
Rice, SRI	0.83	Bangladesh	Duxbury, J.M., cited in McDonald, A.J. et al. 2005. Op. cit.
Rice, SRI	0.82	Bangladesh	Duxbury, J.M., cited in McDonald, A.J. et al. 2005. Op. cit.
Rice, SRI	0.73	Philippines	Rickman, J.F. 2004. Preliminary results: Rice production and the system of rice intensification. Available at Web site: http://ciifad.cornell.edu/sri/countries/philippines/irrieval.pdf
Rice, SRI	0.73	India	Annapurna farm (http://ciifad.cornell.edu/sri/countries/india/)
Rice, SRI	0.64	Thailand	Sooksa-nguan, T., Teaumroong, N., Boonkerd, N., Gypmantasiri, P., and Thies, J.E. 2004. Microbial community activity and structure associated with the system of rice intensification in northern Thailand. In: Soil Science Society of America, 68th Annual Meeting, Seattle, WA.
Rice, SRI	0.63	Laos	GTZ (http://ciifad.cornell.edu/sri/countries/laos/laoritr102.pdf)
Rice, SRI	0.62	Thailand	Gypmantasiri, P. 2002. Op. cit.
Rice, SRI	0.80	Bangladesh	Duxbury, J.M., cited in McDonald, A.J. et al. 2005. Op. cit.
Rice, SRI	0.75	Nepal	Duxbury, J.M., cited in McDonald, A.J. et al. 2005. Op. cit.
Rice, SRI	0.60	Thailand	Gypmantasiri, P. 2002. Op. cit.
Rice, SRI	0.45	Philippines	Rickman, J.F. 2004. Op. cit.
Rice, SRI	0.39	Laos	NRRP (http://ciifad.cornell.edu/sri/countries/laos/laoritr102.pdf)
Rice, SRI	1.29	Bangladesh	Uphoff, N. 2003. Higher yields with fewer external inputs? The system of rice intensification and potential contributions to agricultural sustainability. International Journal of Agricultural Sustainability 1:38–50.
Rice, SRI	1.78	Cambodia	Uphoff, N. 2003. Op. cit.
Rice, SRI	1.14	China	Uphoff, N. 2003. Op. cit.
Rice, SRI	1.58	Cuba	Uphoff, N. 2003. Op. cit.
Rice, SRI	3.09	Gambia	Uphoff, N. 2003. Op. cit.
Rice, SRI	1.48	Indonesia	Uphoff, N. 2003. Op. cit.
Rice, SRI	2.77	Madagascar	Uphoff, N. 2003. Op. cit.
Rice, SRI	2.95	Madagascar	Uphoff, N. 2003. Op. cit.
Rice, SRI	2.00	Philippines	Uphoff, N. 2003. Op. cit.
Rice, SRI	2.12	Sierra Leone	Uphoff, N. 2003. Op. cit.
Rice, SRI	2.17	Sri Lanka	Uphoff, N. 2003. Op. cit.
Rice, upland	2.80	India	Pretty, J. and Hine, R. 2001. Op. cit.
Rice, upland	1.87	India	Pretty, J. and Hine, R. 2001. Op. cit.

Table A1. Continued.

Crop	Yield ratio	Location	Reference
Rice, upland	3.40	Nepal	Pretty, J. and Hine, R. 2001. Op. cit.
Rice, upland	1.50	Nepal	Pretty, J. and Hine, R. 2001. Op. cit.
Rice, upland	1.23	Pakistan	Wai, O.K. 1995. Food, culture, trade and the environment in Asia. Ecology and farming (published by International Federation of Organic Agriculture Movements) 10:22–26.
Rice, upland	1.13	Philippines	Pretty, J. and Hine, R. 2001. Op. cit.
Sorghum	1.65	India	Pretty, J. and Hine, R. 2001. Op. cit.
Sorghum/Millet	2.10	Burkina Faso	Pretty, J. and Hine, R. 2001. Op. cit.
Sorghum/Millet	3.50	India	Pretty, J. and Hine, R. 2001. Op. cit.
Sorghum/Millet	1.76	India	Pretty, J. and Hine, R. 2001. Op. cit.
Sorghum/Millet	2.12	India	Pretty, J. and Hine, R. 2001. Op. cit.
Sorghum/Millet	2.25	India	Pretty, J. and Hine, R. 2001. Op. cit.
Sorghum/Millet	5.67	Mali	Pretty, J. and Hine, R. 2001. Op. cit.
Sorghum/Millet	1.71	Niger	Pretty, J. and Hine, R. 2001. Op. cit.
Sorghum/Millet	2.35	Senegal	Pretty, J. and Hine, R. 2001. Op. cit.
Sorghum/Teff	1.50	Ethiopia	Pretty, J. and Hine, R. 2001. Op. cit.
Wheat	1.17	China	Pretty, J. and Hine, R. 2001. Op. cit.
Wheat	1.17	Pakistan	Pretty, J. and Hine, R. 2001. Op. cit.
Wheat	1.25	Pakistan	Wai, O.K. 1995. Op. cit.
Starchy roots			
Cassava	1.30	Cuba	Ruiz, L. 1993. Factores que condicionan la eficiencia de las micorrizas arbusculares, como alternativa para la fertilización de las raíces y tubérculos tropicales. Dissertation, Agricultural University of Havana (UNAH), Havana.
Cassava	1.75	Ghana	Pretty, J. and Hine, R. 2001. Op. cit.
Potatoes	1.50	Bolivia	Pretty, J. and Hine, R. 2001. Op. cit.
Potatoes	3.50	Bolivia	Pretty, J. and Hine, R. 2001. Op. cit.
Potatoes	1.43	Peru	Altieri, M. 1999. Op. cit.
Potatoes	3.08	Peru	Pretty, J. and Hine, R. 2001. Op. cit.
Potatoes	4.40	Peru	Pretty, J. and Hine, R. 2001. Op. cit.
Potatoes	1.60	Peru	Pretty, J. and Hine, R. 2001. Op. cit.
Sweet Potato	5.83	Ethiopia	Pretty, J. and Hine, R. 2001. Op. cit.
Sweet Potato	3.78	Indonesia	Pretty, J. and Hine, R. 2001. Op. cit.
Sweet Potato	1.50	Indonesia	Pretty, J. and Hine, R. 2001. Op. cit.
Legumes (pulses)			
Beans	5.67	Honduras	Bunch, R. 1999. More productivity with fewer external inputs: Central American case studies of agroecological development and their broader implications. Environment, Development and Sustainability 1:219–233.
Beans	2.32	Honduras	Pretty, J. and Hine, R. 2001. Op. cit.
Oil crops			
Peanut	1.64	Senegal	Altieri, M. and Uphoff, N. 2001. Alternatives to conventional modern agriculture for meeting food needs in the next century. Cornell International Institute for Food, Agriculture, and Development. Available at Web site: http://ciifad.cornell.edu/documents/bellagioenglish.pdf.
Soybean	1.65	Brazil	Pretty, J. and Hine, R. 2001. Op. cit.
Vegetables			
Cabbage	1.21	Philippines	Pretty, J. and Hine, R. 2001. Op. cit.
Vegetables	1.39	Bangladesh	Pretty, J. and Hine, R. 2001. Op. cit.
Vegetables	4.15	Chile	Pretty, J. and Hine, R. 2001. Op. cit.
Vegetables	2.00	Kenya	Pretty, J. and Hine, R. 2001. Op. cit.
Vegetables	1.48	Malawi	Pretty, J. and Hine, R. 2001. Op. cit.
Vegetables	2.00	Zimbabwe	Pretty, J. and Hine, R. 2001. Op. cit.
Fruits			
Fruit	1.25	Cuba	Treto, E., M. García, R.M. Viera, J.M. Febles. 2002. Advances in organic soil management. In F. Funes, L. García, M. Bourque, N. Pérez, and P. Rosset (eds). Sustainable Agriculture and Resistance: Transforming Food Production in Cuba. Food First Books, Oakland, CA. p. 164–189.

Table A1. Continued.

Crop	Yield ratio	Location	Reference
Banana/Plantain	1.90	Uganda	Pretty, J. and Hine, R. 2001. Op. cit.
Banana/Plantain	4.00	Uganda	Pretty, J. and Hine, R. 2001. Op. cit.
Citrus	2.75	Pakistan	Pretty, J. and Hine, R. 2001. Op. cit.
Mango	2.75	Pakistan	Pretty, J. and Hine, R. 2001. Op. cit.
Milk, excl. butter			
Milk	4.00	Cameroon	Pretty, J. and Hine, R. 2001. Op. cit.
Milk	1.60	India	Pretty, J. and Hine, R. 2001. Op. cit.
Milk	2.57	Tanzania	Pretty, J. and Hine, R. 2001. Op. cit.
Milk	4.00	Tanzania	Pretty, J. and Hine, R. 2001. Op. cit.
Milk	1.30	Uganda	Pretty, J. and Hine, R. 2001. Op. cit.

Appendix 2: Nitrogen from Cover Crops

Table A2. Data and sources for nitrogen availability from cover crops; the country where the study occurred is listed when it is known. Multiple entries from the same source represent data for different plant species or varieties. Values with asterisk (*) were calculated based on 66% of the N fixed by a cover crop becoming available for plant uptake during the growing season following the cover crop[34]. The other values are the 'fertilizer-replacement value,' determined as the amount of N fertilizer needed to achieve yields equivalent to those obtained using N from cover crops. Values from studies in the US were the basis for calculating the N available from cover crops for the United States in Table 4.

kg N ha^{-1}	Country	Reference
Temperate ($n = 33$)		
95.0	Canada	Odhiambo, J.J.O. and Bomke, A.A. 2001. Grass legume cover crop effects on dry matter and nitrogen 'Crimson Clover' accumulation. Agronomy Journal 93:299–307.
95.0	US	Balkcom, K.S. and Reeves, D.W. 2005. Sunn-hemp utilized as a legume cover crop for corn production. Agronomy Journal 97:26–31.
82.0	US	Cline, G.R. and Silvernail, A.F. 2002. Effects of cover crops, nitrogen, and tillage on sweet corn. HortTechnology 12:118–125.
94.0	US	Decker, A.M., Holderbaum, J.F., Mulford, R.F., Meisinger, J.J., and Vough, L.R. 1987. Fall-seeded legume nitrogen contributions to no-till corn production. In J.F. Power (ed.). Role of Legumes in Conservation Tillage System: Proceedings of a national conference, University of Georgia, Athens, April 27–29. Soil Conservation Society of America. p. 21–22.
56.0	US	Drinkwater, L.E., Wagoner, P., and Sarrantonio, M. 1998. Legume-based cropping systems have reduced carbon and nitrogen losses. Nature 396:262–265.
95.0	US	Ebelhar, S.A., Frye, W.W., and Belebins, R.L. 1984. Nitrogen From legume cover crops for no-tillage corn. Agronomy Journal 76:51–55.
104.0	US	Groffman, P.M., Hendrix, P.F., and Crossley Jr, D.A. 1987. Nitrogen cycling in conventional and no-tillage agroecosystems with inorganic fertilizer or legume nitrogen inputs. Plant and Soil 97:325–332.
91.0	US	Hargrove, W.L. 1986. Winter legumes as a nitrogen source for no-till grain sorghum. Agronomy Journal 78:70–74.
77.0	US	Herbek, J.H., Frye, W.W., and Blevins, R.L. 1987. Nitrogen from legume cover crops for no-till corn and grain sorghum. In J.F. Power (ed.). Op. cit., p. 51–52.
99.7	US	Holderbaum, J.F., Decker, A.M., Mulford, F.R., Meisinger, J.J., and Vough, L.R. 1987. Forage contributions of winter legume cover crops in no-till corn production. In J.F. Power (ed.). Op. cit., p. 98–99.
105.6	US	Hoyt, G.D. 1987. Legumes as a green manure in conservation tillage. In J.F. Power (ed). Op. cit., p. 96–97.
100.0	US	Hoyt, G.D. and Hargrove, W.L. 1986. Legume cover crops for improving crop and soil management in the southern United States. HortScience 21:397–492.
84.0	US	Leidner, M.B. 1987. Crimson clover and corn: A conservation tillage system that works in Georgia's Coastal Plain. In J.F. Power (ed.). Op. cit., p. 103–104.
62.0	US	Ngalla, C.F. and Eckert, D.J. 1987. Wheat-red clover interseeding as a nitrogen source for no-till corn. In J.F. Power (ed.), Op. cit., p. 47–48.

Table A2. Continued.

kg N ha^{-1}	Country	Reference
79.0	US	Oyer, L.J. and Touchton, J.T. 1987. Nitrogen fertilizer requirements for corn as affected by legume cropping systems and rotations. In J.F. Power (ed.). Op. cit., p. 44–45.
84.0	US	Pettygrove, G.S. and Williams, J.F. 1997. Nitrogen-fixing cover crops for California rice production. University of California Davis Rice Project Web site. http://agronomy.ucdavis.edu/ucce/index.htm.
60.0	US	Pettygrove, G.S. and Williams, J.F. 1997. Nitrogen-fixing cover crops for California rice production. University of California Davis Rice Project Web site. http://agronomy.ucdavis.edu/ucce/index.htm.
40.0	US	Pettygrove, G.S. and Williams, J.F. 1997. Nitrogen-fixing cover crops for California rice production. University of California Davis Rice Project Web site. http://agronomy.ucdavis.edu/ucce/index.htm.
77.8	US	Poudel, D.D., Horwath, W.R., Lanini, W.T., Temple, S.R., and van Bruggen, A.H.C. 2002. Comparison of soil N availability and leaching potential, crop yields and weeds in organic, low-input and conventional farming systems in northern California. Agriculture, Ecosystems and Environment 90:125–137.
99.7	US	Poudel, D.D. et al. 2002. Op. cit.
17.8	US	Reddy, K.C., Soffes, A.R., and Prine, G.M. 1986. Tropical legumes for green manure. I. Nitrogen production and the effects on succeeding crop yields. Agronomy Journal 78:1–4.
92.4	US	Reddy, K.C. et al. 1986. Op. cit.
94.6	US	Reddy, K.C. et al. 1986. Op. cit.
107.8	US	Reddy, K.C. et al. 1986. Op. cit.
110.0	US	Reddy, K.C. et al. 1986. Op. cit.
125.4	US	Reddy, K.C. et al. 1986. Op. cit.
136.4	US	Reddy, K.C. et al. 1986. Op. cit.
101.6	US	Sainj, U.M., Singh, B.P., and Whitehead, W.F. 1998. Cover crop root distribution and its effects on soil nitrogen cycling. Agronomy Journal 90:511–518.
78.0	US	Schmidt, W.H., Myers, D., and Van Keuren, R.W. 1974. Value of legumes for plowdown nitrogen. Agronomy Tip Misc-4. Ohio Cooperative Extension Service, Columbus, Ohio.
231.0	US	Schulz, S., Keatinge, J.D.H., and Wells, G.J. 1999. Productivity and residual effects of legumes in rice-based cropping systems in a warm-temperate environment. II. Residual effects on rice. Field Crops Research 61:37–49.
171.6	US	Stivers, L.J., Shennan, C., Jackson, L.E., Groddy, K., Griffin, C.J., and Miller, P.R. 1993. Winter cover cropping in vegetable production systems in California. In M.G. Paoletti, W. Foissner, and D. Coleman (eds). Soil Biota Nutrient Cycling and Farming Systems. Lewis Publishers, Boca Raton, FL, p. 227–240.
68.0	US	Touchton, J.T., Rickerl, D.H., Walker, R.H., and Snipes, C.E. 1984. Winter legumes as nitrogen source for no-tillage cotton. Soil and Tillage Research 4:391–401.
123.0	US	Tyler, D.D., Duck, B.N., Graveel, J.G., and Bowen, J.F. 1987. Estimating response curves of legume nitrogen contribution to no-till corn. In J.F. Power (ed.). Op. cit., p. 50–51.
95.1		Average for temperate studies ($n = 33$)
Tropical ($n = 43$)		
16.5		Peoples, M.B., Herridge, D.F., and Ladha, J.K. 1995. Biological nitrogen fixation: an efficient source of nitrogen for sustainable agricultural production? Plant and Soil 174:3–28.
52.1		Peoples, M.B. et al. 1995. Op. cit.
66.7		Peoples, M.B. et al. 1995. Op. cit.
88.1		Peoples, M.B. et al. 1995. Op. cit.
99.0		Peoples, M.B. et al. 1995. Op. cit.
101.3		Peoples, M.B. et al. 1995. Op. cit.
130.0		Peoples, M.B. et al. 1995. Op. cit.
141.2		Peoples, M.B. et al. 1995. Op. cit.
176.2		Rinaudo, G., Dreyfus, B., and Dommergues, Y. 1983. *Sesbania rostrata* green manure and the nitrogen content of rice crop and soil. Soil Biology and Biochemistry 15: 111–113.
85.3	Brazil	Ambrosano, E.J. et al. 2005. Utilization of nitrogen from green manure and mineral fertilizer by sugarcane. Sci. Agric. (Piracicaba, Brazil) 62:534–542.
55.0	Colombia	Cobo, J.G., Barrios, E., Kass, D.C.L., and Thomas, R.J. 2002. Decomposition and nutrient release by green manures in a tropical hillside agroecosystem. Plant and Soil 240:331–342.
59.3	Colombia	Cobo, J.G. et al. 2002. Op. cit.
60.1	Colombia	Cobo, J.G. et al. 2002. Op. cit.
72.4	Colombia	Cobo, J.G. et al. 2002. Op. cit.
76.4	Colombia	Cobo, J.G. et al. 2002. Op. cit.

Table A2. Continued.

kg N ha^{-1}	Country	Reference
76.5	Colombia	Cobo, J.G. et al. 2002. Op. cit.
85.7	Colombia	Cobo, J.G. et al. 2002. Op. cit.
86.4	Colombia	Cobo, J.G. et al. 2002. Op. cit.
95.4	Colombia	Cobo, J.G. et al. 2002. Op. cit.
94.4	Cuba, Brazil	Ramos, M.G., Villatoro, M.A.A., Urquiaga, S., Alves, B.J.R., and Boddey, R.M. 2001. Quantification of the contribution of biological nitrogen fixation to tropical green manure crops and the residual benefit to a subsequent maize crop using ^{15}N-isotope techniques. Journal of Biotechnology 91:105–115.
56.1	India	Becker, M., Ladha, J.K., and Ali, M. 1995. Green manure technology: potential usage and limitations. A case study for lowland rice. Plant and Soil 174:181–194.
78.0	India	Ghai, S.K., Rao, D.L.N., and Batra, L. 1988. Nitrogen contribution to wetland rice by green manuring with *Sesbania* spp. in an alkaline soil. Biology and Fertility of Soils 6:22–25.
122.0	India	Ghai, S.K. et al. 1988. Op. cit.
104.3	India	Rao, D.L.N. and Gill, H.S. 1993. Nitrogen fixation, biomass production, and nutrient uptake by annual *Sesbania* species in an alkaline soil. Biology and Fertility of Soils 15:73–78.
75.9	Nigeria	Iberwiro, B., Sanginga, N., Vanlauwe, B., and Merckx, R. 2000. Evaluation of symbiotic dinitrogen inputs of herbaceous legumes into tropical cover-crop systems. Biology and Fertility of Soils 32:234–242.
64.4	Nigeria	Mulongoy, K. 1986. Microbial biomass and maize nitrogen uptake under a *Psophocarpus palustris* live-mulch grown on a tropical alfisol. Soil Biology and Biochemistry 18:395–398.
107.2	Philippines	George, T., Ladha, J.K., Garrity, D.P., and Torres, R.O. 1995. Nitrogen dynamics of grain legume-weedy fallow-flooded rice sequences in the tropics. Agronomy Journal 87:1–6.
101.3	Philippines	Pareek, R.K., Ladha, J.K., and Wantanabe, I. 1990. Estimating N_2 fixation by *Sesbania rostrata* and *S. cannabina* in lowland rice soil by the ^{15}N dilution method. Biology Fertility of Soils 10:77–88.
29.7	Philippines	Thonnissen, C., Midmore, D.J., Ladha, J.K., Olk, D.C., and Schmidhalter, U. 2000. Legume decomposition and nitrogen release when applied as green manures to tropical vegetable production systems. Agronomy Journal 92:253–260.
82.5	Philippines	Thonnissen, C. et al. 2000. Op. cit.
60.0	Philippines	Torres, R.O., Pareek, R.P., Ladha, J.K., and Garrity, D.P. 1995. Stem-nodulating legumes as relay-cropped or intercropped green manures for lowland rice. Field Crops Research 42:39–47.
423.0	Senegal	Alazard, D. and Becker, M. 1987. *Aeschynomene* as green manure for rice. Plant and Soil 101:141–143.
532.0	Senegal	Alazard, D. and Becker, M. 1987. Op. cit.
82.5	South Asia	Ladha, J.K., Pareek, R.P., and Becker, M. 1992. Stem-nodulating legume-*Rhizobium* symbiosis and its agronomic use in lowland rice. Advances in Soil Science 2:147–192.
174.2	South Asia	Ladha, J.K. et al. 1992. Op. cit.
145.2	South Asia	Ladha, J.K., Kundu, D.K., Coppenolle, M.G.A., Peoples, M.B., Carangal, V.R., and Dart, P.J. 1996. Legume productivity and soil nitrogen dynamics in lowland rice-based cropping systems. Soil Science Society of America Journal 6:183–192.
139.3	South Asia	Ladha, J.K. et al. 1996. Op. cit.
139.3	South Asia	Ladha, J.K. et al. 1996. Op. cit.
60.7	Sri Lanka	Palm, O., Weerakoon, W.L., de Silva, M.A.P., and Rosswall, T. 1988. Nitrogen mineralization of *Sesbania sesban* used as green manure for lowland rice in Sri Lanka. Plant and Soil 108:201–209.
110.6	Syria	Sultan, K., Ginntzburger, G., Obaton, M., Robin, C., Touchane, H., and Guckert, A. 2001. Growth and nitrogen fixation of annual *Medicago-Rhizobium* associations during winter in Mediterranean region. European Journal of Agronomy 15:221–229.
103.6	US	Rotar, P.P. and Joy, R.J. 1983. ‘Tropic Sun’ sunn hemp *Crotalaria juncea* L. Research Series, 36. Hawaiian Institute of Tropical Agriculture and Human Resources, University of Hawaii, Honolulu.
95.0	Uganda	Wortmann, C.S., McIntyre, B.D., and Kaizzi, C.K. 2002. Annual soil improving legumes: agronomic effectiveness, nutrient uptake, nitrogen fixation and water use. Field Crops Research 68:75–83.
66.0	West Africa	Carsky, R.J., Jagtap, S., Tian, G., Sanginga, N., and Vanlauwe, B. 1998. Maintenance of soil organic matter and nitrogen supply in the moist savanna zone of West Africa. In R. Lal (ed). Soil and Agricultural Sustainability. Sleeping Bear Press, Chelsea, MI.
108.6		Average for tropical studies ($n = 43$)
102.8		Average for all studies ($n = 76$)