The paper cites four separate favorable yield ratios for wheat from the first 3 years of a long-term California research project (McGuire et al., 1998), but they omit the drastically lower organic maize yields from the same project reported in 2004. The non-organic maize yields were 52% higher than the organic from 1996 to 2004. This result in particular calls into question one of the Michigan group's major claims: that organic farming can obtain ample nitrogen by growing off-season green-manure crops to replace the inorganic synthetic nitrogen fertilizer that currently underpins roughly half of global crop production. In this case, the legume crop costs half the ensuing corn crop. Thus, the green-manure strategy, implemented worldwide, threatens a major cropland expansion due to lower per acre yields and the ensuing loss of wildlife habitat and biodiversity.

Moreover, while there were 'no statistical differences in tomato yields among [the different systems]' during those 8 years, conventional irrigated wheat yields were nearly 30% higher than irrigated 'organic' wheat over the same period.

Many of the studies cited by Badgley et al. are from organic activists with a clear agenda in reporting only high organic yields. The Michigan researchers call these sources 'grey literature', but a more accurate term would be 'biased observers with a clear economic and reputational stake in the outcome'.

For example, there are numerous yield ratios gleaned from reports from 'biodynamic' societies such as the Anthroposophic Society, the Institute for Biodynamic Research, and anti-GM/anti-conventional agriculture pressure groups such as Food First.

This clearly skews the results. A recurrent source for 'developed country' yield ratios is an article written by Bill Liebhardt, published in the quarterly newsletter of an organic promotion organization. Liebhardt cites a 0.95 yield ratio for organic maize following a legume–soybean rotation in comparison to continuous maize yields—despite the fact that the same research Liebhardt cites shows that non-organic maize following soybeans out-yields organic by 10–30%. This is a clear case of favoring the organic perspective.

More egregiously, Liebhardt combines tomato yields from two separate projects to claim 'equal' organic tomato yields when the studies he cites found organic tomato yields were significantly lower yielding. In the first 3 years of one project, non-organic tomatoes out-yielded organic by 66%. So in the fourth year, the researchers started giving the organic tomatoes a literal head start by transplanting tomato plants started weeks earlier in a greenhouse—while still using tomato seeds in the non-organic plots. Yet the non-organic tomatoes continued to out-yield the organic by an average of 20% in the following 4 years. So in year 7 of the project, the researchers tripled the amount of poultry manure applied to the organic plots, giving the organic tomatoes 3–4 times more nitrogen than the non-organic. Only after all these changes did the organic tomato yields surpass the non-organic by 9%. Even then, organic fruit quality was lower, used more irrigation water, had far greater weed problems, and cost hundreds of dollars more per acre to grow—losing money without a high price premium.

Misreporting of Yields

The authors simply misreport organic yields compared to conventional in at least one instance. Badgley et al. report that organic apples achieve 100% equal yields (ratio of 1.00) in a study published in *Nature* (Reganold et al. 2001. Nature 410:926–930). The study actually reported that organic apples achieved only 93% of non-organic yields (ratio of 0.93).

Strengthening the case for organic agriculture: response to Alex Avery

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Response

The paper by Badgley et al. (2007), 'Organic agriculture and the global food supply' (RAFS 22(2):86–108), presents the case that organic agriculture has the potential to feed the current human population. This conclusion comes from an analysis of 293 yield ratios comparing organic to non-organic production in studies from around the world. In addition, we present data from temperate and tropical agroecosystems showing that leguminous cover crops grown

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between normal cropping periods could fix more nitrogen than all the synthetic nitrogen currently in use. Our study demonstrates that farmers, consumers, and policy-makers have substantial viable alternatives about how to feed the world, now and in the future. The potential of organic methods is great enough to merit serious consideration by farmers, extension services, agricultural ministries, and global advisory bodies, such as the United Nations Food and Agriculture Organization (FAO), looking at the food security of their regions or the world.

Alex Avery from the Hudson Institute is spreading false and misleading claims about this study.

Response to Alex Avery

Alex Avery presents five criticisms of the paper by Badgley et al. (2007). We respond to each in turn. Numbered items in *italics* and paragraphs in quotes are from Avery's critique.

1. Non-organic yields are used to inflate organic productivity

> 'In perhaps the most brazen example of research misrepresentation in decades, 105–119 studies claimed as "organic" by the University of Michigan group were not organic.'

In the introduction of the paper, we describe how we use the term 'organic' in our study.

> *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*. [p. 87, second paragraph]

We used a broader meaning of organic than that of any particular certification program so that we could legitimately include studies that involve practices that are substantially in the direction of strict organic. These studies are from the developing world, where yield comparisons are otherwise quite scarce.

> 'The researchers did not provide enough detail to determine the exact number of misrepresented studies, but their main source (Pretty and Hine, 2001) stated clearly in their reports that only 14 of 208 studies in their database are "organic".'

The general methods by which farm productivity increased in the case studies documented by Pretty and Hine (2001) include intensification of one component of the farm system (e.g., biointensive vegetable gardens, multilayer tree gardens), addition of a new element (animals or trees), better use of natural capital (water or reclamation of degraded land), new regenerative elements (legumes, integrated pest management), and use of new locally appropriate varieties or breeds (p. 13). The authors state 'By our definition of sustainability, almost all projects have made substantial use of agro-ecological or organic principles in production processes' (Annex B, Part 6). This description persuaded us that the 70 cases we cited from Pretty and Hine were from farms practicing methods close to organic. We did not utilize all of the data in this source; for some crops and management practices, we found more detailed information in other sources. If yield information was not tied to a specific crop in a particular country in a particular location, then we did not include it.

> 'As an example, Badgley et al. claim organic methods increased Argentine maize yields by 37% (source: Roberto Pieretti in "Pretty and Hine, 2001"). In fact, this statistic comes from Argentine farmers using herbicides to kill weeds, growing GMO herbicide-tolerant soy and GMO insect- and herbicide-resistant maize, and extensively using synthetic fertilizers and organic-prohibited pesticides. To label these yield gains as "organic" is absurd'.

The yield ratio for maize from Argentina (1.37) is the correct value cited in Pretty and Hine in Table 14, Annex C. The elaboration of this case study (Annex D, Latin America, No. 1) describes zero-till farming. 'Farmers use a range of Integrated Pest Management (IPM), rotational and precision methods for pest and nutrient management. For example, black oats are now commonly used in the rotation during winter for both soil cover and weed suppression. Other legume cover crops are used to improve nitrogen supplies' (Annex D, p. 109). No mention of genetically modified (GM) crops is given. Avery's claim does not fit the information presented in the report of Pretty and Hine. We did not cite the value for soy from Argentina, even though one is given, since so much Argentine soy is GM.

> 'Another misrepresentation is China maize yield increase of 38%, reported from the East Gansu project run by the Chinese government. The primary source (Pretty and Hine, 2001) reports that "Grain output and food per capita [in the project area] have increased greatly because of improved crops varieties, runoff harvesting and water-saving irrigation, ***and fertilizers and pesticide use***" [emphasis added].'

The example from East Gansu includes the following passage: 'Additional benefits [of more efficient rainfall capture and storage, mulching, multiuse crop products and bi-products for livestock] include reduced soil erosion, decreased pesticide and fertilizer use, increased social capital formation ...' (Pretty and Hine, 2001, Annex D, Asia, example 4). This description indicated to us that these practices were substantially in the direction of organic methods.

> 'They also labeled as "organic" 49 yield ratios from the "System of Rice Intensification" which is not organic.'

For studies involving the System of Rice Intensification (SRI), the yield ratios that we used were either organic (as described in the sources) or implied to be organic. For studies reporting comparisons between organic SRI and non-organic methods, we calculated our yield ratio based on the comparison between organic and non-organic practices. According to Norman Uphoff, an expert on SRI, the SRI method is usually organic.

We note also the statistical analysis presented in Appendix 1 of our paper. To investigate the possibility that data from Pretty and Hine were biasing the average yield ratio for general food categories, we ran a *t*-test on yield ratios from surveys and unreported methods compared to yield ratios from experiments and quantitative comparisons (see p. 97, column 2 of our article). We performed the *t*-test on data for grains, for which the sample size was largest. (Also, since grains provide most of the calories that people consume, the test matters the most for this food category.) The *t*-test failed to find a statistically significant difference between the average yield ratios for data from surveys + unreported methods and data from experiments + quantitative comparisons. This test demonstrates that the data from Pretty and Hine did not bias our results for the developing world.

In summary, we consider that we explained our use of 'organic' and gathered data consistently with our stated usage.

2. False comparison with low non-organic yields

> 'The amazingly high yield increases reported in the developing world should have been a red flag that the non-organic yields used in the comparisons were uncommonly low.'

As stated in our paper, for the developing world, we compared studies of organic methods of intensification with primarily traditional, low-input agriculture. This kind of agriculture usually does exhibit low yields; our point is that organic intensification will improve them.

> 'For example, Badgley et al. report one study where Peruvian organic potato yields were 340% higher than non-organic (yield ratio of 4.40). Yet the "higher" organic potato yields (reported as "8000 to 14,000 kg/ha", or 11,000 average) are below the year-2000 average potato yield for Peru, reported by the United Nations Food and Agriculture Organization at 11,221 kg/ha in the year 2000. Many farmers in developing countries using non-organic methods report potato yields well above 15,000 kg/ha and non-organic potato yields in developed countries are routinely above 40,000 kg/ha—each considerably higher than the "high" organic potato yields.'

We did not compare our yield ratios to country averages for any food categories, nor do we consider this an appropriate comparison for any of our data. The Peruvian potato examples cited in Pretty and Hine were from high-elevation marginal environments—which were not representative of country average values. (As a side note, the 11,000 kg/ha average reported in Pretty and Hine is statistically indistinguishable from the country average of 11,221 kg/ha—if one were to undertake a serious comparison.) The strength of our analysis is in using the many yield comparisons to evaluate average yield ratios for general food categories. A much larger dataset of a different nature could estimate how much of a particular crop could be grown in a particular country. Hence, this criticism is not valid for our paper.

3. Multiple counting of yields from the same research projects

> 'The paper claims to analyze a "global dataset of 293 examples", yet there are numerous instances of repeated counting of yields from the same long-term studies.'

We were alert to this possibility and weeded out a few replicates at an early stage, then checked again once our dataset was complete. Within a source, we averaged values reported for one treatment method but reported different treatments (e.g., corn/soy versus corn/soy/wheat) separately.

> 'For example, the maize yields from the long-term Farming Systems Trial project conducted by the pro-organic Rodale Institute (Kutztown, PA, USA) are reported four times: once in a "case study" in a 1989 report from the National Research Council, twice in a report from Pimentel et al., and once in a 2001 newsletter article by Bill Liebhardt.'

Rodale's Farm Systems Trial was initiated in 1981. The experimental design was changed several times and stabilized in 1991. Since 1991, the Farm Systems Trial has had three treatments: conventional, organic with manure, and organic with cover crops (Pimentel et al. 2005). The data reported by Pimentel et al. are from 1981–2002; one of the central points of this analysis of 22 years of data for the Farm Systems Trial is that the yields (absolute and relative) from the three treatments have changed over time. The data for each treatment are different. For corn and soy (present in all three treatments), we counted the organic-manure/conventional and the organic-cover crop/conventional as separate values. This is not double-counting, and the values are not the same. The value reported from Liebhardt (2001) is an average of data from studies in seven states, with 69 cropping seasons. One of the sources mentioned is the Rodale study, with data for 1990–1999 via personal communication; none of the other studies mentioned by Liebhardt for maize are cited by us, although we cite some of the same authors for different studies. The average from Liebhardt is dominated by the non-Rodale studies—hence an example of substantial non-equivalence. The data from the 1989 book by the National Research Council come from Case Study 4, the Kutztown Farm, and more specifically from a study by Culik et al. about this farm. The area evaluated includes land from the Rodale Research Center, the actual Kutztown farm, and land from an adjacent farm. The data come from 1978–1982. The study of Culik et al. could be considered the precursor to the Farm Systems Trial, which was begun in 1981 on the Rodale Research Land. Comparison of the treatments of the Farm Systems Trial (as reported in Pimentel et al. 2005) and the treatments reported from Culik et al. (in the book by the National Research Council) shows that these differ substantially for corn. The Farm Systems Trial follows a rigid rotation pattern in a block design of 24 plots; the Kutztown farm (on a larger land base) uses a variable rotation of corn with hay depending on the weather, weeds, insects, and soil fertility of the specific fields. It is not the same system. It would not be appropriate to average all the data from different treatments. Thus, there is no repetition of data (and all the values differ).

> 'Soy yields from the same Rodale FST project are reported five times: once by the 1989 NRC report, once by Liebhardt, once by Hanson et al., and twice by Pimentel et al.'

With regard to soy yields, values from two different treatments (as explained above) were taken from Pimentel et al. (2005). The data from Liebhardt (2001) are from studies in five states, including the Rodale Farm Systems Trial from 1990–1999. The data taken from the National Research Council are from the Kutztown farm—different land, different years, and different treatment than the Farm Systems Trial. The data from Hanson et al. (1997) are from 1986–1990, under a different rotation schedule than for the years 1991 to the present. Thus, a careful evaluation of the sources shows that there is no replication for these data. Avery's criticism on this point is unfounded.

4. Omitting non-favorable crop yields and cherry-picking data

> 'The paper reports the favorable yields of specific organic crops from research, while omitting the unfavorable yields of other crops reported in the same research. In addition, non-favorable study results from organic research groups were entirely omitted.'

This claim is untrue. An examination of our data shows that there are many low yield ratios, especially for studies in developed countries. For grains, we have yield ratios as low as 0.55 (wheat, Michigan) and similarly low values in other food categories (e.g., 0.55 for tomatoes from Ontario). Some of our low ratios come from papers critical of organic agriculture (e.g., Trewavas, 2004). We made a substantial effort to assemble representative, unbiased samples.

> 'Four different favorable potato yield ratios are cited from one research project in Germany (90–106% of non-organic yields), while unfavorable organic potato yield data (75% of non-organic potato yields) published in the very same journal in which the Badgley paper appeared was omitted! (Gallandt et al. 1998. American Journal of Alternative Agriculture 13:146–161, which is now *Renewable Agriculture and Food Systems*).'

We appreciate learning about the potato study of Gallandt et al. (1998). However, if we add the 0.75 ratio from that study to our dataset on yield ratios, it affects the third decimal place of our average yield ratio for the vegetable food category. Thus, omission of data from this study does not change our general conclusions. As a side note, the potato study documented in Gallandt et al. 1998 (in Maine, USA) was redesigned in 1998 for comparisons based on different soil amendments, different weed and pest management strategies, and different rotations. In summarizing long-term results from the same study, Mallory and Porter (2007. Agronomy Journal 99:501–500) reported that potato yields in 12 of 13 years in amended systems (manure, compost, green manure, with minimal synthetic fertilizer inputs) were equal to or higher (4–55%) than in the conventional fertilizer management system. The soil management system relying more on organic inputs improved soil quality and reduced the year-to-year variability in potato yields. While these data cannot be used to confirm actual yield ratios between organic and conventional management, they do clearly demonstrate the advantage to yield quantity, stability and soil quality of using organic and ecological approaches.

> 'The paper cites four separate favorable yield ratios for wheat from the first 3 years of a long-term California research project (McGuire et al., 1998), but they omit the drastically lower organic maize yields from the same project reported in 2004. The non-organic maize yields were 52% higher than the organic from 1996 to 2004.'

The follow-up study to McGuire et al. (1998) is Denison et al. (2004. Field Crops Research 86:267–277). Mean crop yields of maize in organic versus conventional treatments resulted in a yield ratio of 0.66 for 1996–2002. From the same study, mean crop yields of tomato in organic versus conventional treatments resulted in a yield ratio of 1.11 for 1996–2002. Adding these data to our dataset would lead to a slight decrease in the average yield ratio for grain and a slight increase in the average yield ratio for vegetables (in the third decimal place). Neither change would alter the overall conclusions of our study.

> 'This result in particular calls into question one of the Michigan group's major claims: that organic farming can

'obtain ample nitrogen by growing off-season green-manure crops to replace the inorganic synthetic nitrogen fertilizer that currently underpins roughly half of global crop production. In this case, the legume crop costs half the ensuing corn crop. Thus, the green-manure strategy, implemented worldwide, threatens a major cropland expansion due to lower per acre yields and the ensuing loss of wildlife habitat and biodiversity.'

Our calculations were based on green manures grown between normal cropping periods; this approach would not require additional cropland. The proposition that green manures could provide adequate nitrogen fertility for grains and other crops was presented not as a prescriptive statement but as a demonstration of the potential for organic sources of fertility to provide the nitrogen needed to grow crops. This method is working well at the Rodale Farm Systems Trial. We would not expect green manures to work the same way in all other settings, nor for the configuration of the sustainable system to be evident in just a few growing seasons. How well green manures will work under other climates and soils and for other crops requires just the sort of research being conducted in the LTRAS at UC Davis. Other organic methods of fertility management are available as a complement or alternative to cover crops.

'Many of the studies cited by Badgley et al. are from organic activists with a clear agenda in reporting only high organic yields. The Michigan researchers call these sources "grey literature", but a more accurate term would be "biased observers with a clear economic and reputational stake in the outcome".'

Most studies cited are from academics who have the experience and credibility to investigate yield comparisons using acceptable scientific procedures. Most studies are reported in reputable scientific journals, including *Nature*, *Science*, *Field Crops Research*, *Agricultural Systems*, *Livestock Production Science*, *Agriculture, Ecosystems and Environment*, *Meat Science*, *Journal of Sustainable Agriculture*, and *American Journal of Alternative Agriculture* (this journal).

'For example, there are numerous yield ratios gleaned from reports from "biodynamic" societies such as the Anthroposophic Society, the Institute for Biodynamic Research, and anti-GM/anti-conventional agriculture pressure groups such as Food First.'

The few studies from biodynamic research organizations were included only if the experimental design was described and followed standard scientific practices. We declined to include data from such sources when this was not the case. Only one yield ratio was taken from a source published by Food First. This was an edited volume about agriculture in Cuba; the Cuban authors are agronomists. A considerable amount of research in organic methods is being conducted in Cuba; thus we considered the data appropriate for this study. The cited "gray literature" investigators who are committed to organic (and other agroecological) farming methods conducted controlled experiments that have as much scientific validity as properly controlled experiments from researchers committed to conventional agriculture.

'A recurrent source for "developed country" yield ratios is an article written by Bill Liebhardt, published in the quarterly newsletter of an organic promotion organization. Liebhardt cites a 0.95 yield ratio for organic maize following a legume–soybean rotation in comparison to continuous maize yields—despite the fact that the same research Liebhardt cites shows that non-organic maize following soybeans out-yields organic by 10–30%. This is a clear case of favoring the organic perspective.'

For the claims about Bill Leibhardt's research, please refer to his response below.

5. Misreporting of yields

'The authors simply misreport organic yields compared to conventional in at least one instance. Badgley et al. report that organic apples achieve 100% equal yields (ratio of 1.00) in a study published in *Nature* (Reganold et al. 2001. Nature 410:926–930). The study actually reported that organic apples achieved only 93% of non-organic yields (ratio of 0.93).'

The figure 93% is mentioned neither in the paper nor in the supplementary information online. Reganold et al. (2001) provide a graph but no numerical data for the yield comparisons between three treatments for apple production. Figure 1 shows that the organic system yielded more than the conventional or integrated systems during 2 years and less during 3 years of a 5-year study. A histogram of cumulative yields over 5 years could be the basis for interpreting organic/conventional as 93%. (Note that the ratio of cumulative yields is not the same as the ratio of yearly averages, which would be more appropriate from this study.) Statistical analysis presented in the paper shows that the organic and conventional yields were statistically indistinguishable. The text states that all three systems gave similar yields (abstract and main text). In the absence of quantitative yield data in either the published paper or supplementary information online, we used a yield ratio of 1.00. Had we used the figure 0.93 instead, the average yield ratio for fruit as a food category for the developed world would have declined by 0.035 to 0.92. This value is the same as the average yield ratio for all plant and animal foods from the developed world ($n = 160$). This change would have negligible impact on our overall results.