2664 *J. Agric. Food Chem.* **2007,** *55,* 2664–2670

JOURNAL OF
AGRICULTURAL AND
FOOD CHEMISTRY

Nitrogen Isotope Composition of Organically and Conventionally Grown Crops

ALISON S. BATEMAN,[†] SIMON D. KELLY,*,[†,§] AND MARK WOOLFE[#]

School of Environmental Sciences, University of East Anglia, Norwich NR4 7TJ, United Kingdom;
Institute of Food Research, Norwich Research Park, Colney, Norwich NR4 7UA, United Kingdom;
and Food Standards Agency, Aviation House, 125 Kingsway, London WC2B 6NH, United Kingdom

Authentic samples of commercially produced organic and conventionally grown tomatoes, lettuces, and carrots were collected and analyzed for their δ^{15}N composition in order to assemble datasets to establish if there are any systematic differences in nitrogen isotope composition due to the method of production. The tomato and lettuce datasets suggest that the different types of fertilizer commonly used in organic and conventional systems result in differences in the nitrogen isotope composition of these crops. A mean δ^{15}N value of 8.1‰ was found for the organically grown tomatoes compared with a mean value of −0.1‰ for those grown conventionally. The organically grown lettuces had a mean value of 7.6‰ compared with a mean value of 2.9‰ for the conventionally grown lettuces. The mean value for organic carrots was not significantly different from the mean value for those grown conventionally. Overlap between the δ^{15}N values of the organic and conventional datasets (for both tomatoes and lettuces) means that it is necessary to employ a statistical methodology to try and classify a randomly analyzed "off the shelf" sample as organic/conventional, and such an approach is demonstrated. Overall, the study suggests that nitrogen isotope analysis could be used to provide useful "intelligence" to help detect the substitution of certain organic crop types with their conventional counterparts. However, δ^{15}N analysis of a "test sample" will not provide unequivocal evidence as to whether synthetic fertilizers have been used on the crop but could, for example, in a situation when there is suspicion that mislabeling of conventionally grown crops as "organic" is occurring, be used to provide supporting evidence.

KEYWORDS: Nitrogen; isotope; organic; conventional; δ^{15}N

INTRODUCTION

To be labeled and sold as "organic", products must be produced and processed in accordance with a set of standards. The International Federation of Organic Agriculture Movements (IFOAM) has a set of Basic Standards for Organic Production and Processing designed as a framework around which national and international organic standards can be built (*1*). However, there are currently about 100 different standards for organic agricultural production around the world (*2*). Across the European Union (EU), Regulation (EEC) 2092/91 sets out the inputs and practices that may be used in organic farming and growing and the accreditation and inspection systems that must be in place to ensure that these conditions are met (*3*). Organic products imported into the EU must also meet standards equivalent to those of Regulation 2092/91. Similar systems exist in other countries, for example, the National Organic Program Regulations in the United States, the Canadian National Standard for Organic Agriculture, and the Australian Organic Standard.

Globally, the market for organic produce continues to grow, not only in Europe and North America (which are the major markets), but also in many other countries including several developing countries. In 2004, the market value of organic products worldwide reached U.S. $27.8 billion (EUR 23.5 billion), and continued growth of the market and the amount of land managed organically is expected for the foreseeable future (*4*).

Organic products usually sell for higher prices than the same goods produced conventionally. Higher prices obtained by producers, wholesalers, and retailers for organic commodities provide an economic incentive for the unscrupulous to mislabel and pass off conventionally grown produce as organic. Over the past two decades, the organic sector has transformed from loosely co-ordinated networks of small growers selling produce locally, when the buyer may have known the grower or the farm on which the produce was grown, to a global system of regulated trade often linking socially and spatially distant sites of production and consumption (*5*). The authenticity of organic products currently relies on enforcement of production standards through certification and inspection. The system depends on traceability through paper trails from farm to fork, and the

---

* Corresponding author [telephone +44 (0)1603 251421; fax +44 (0)-1603 507723; e-mail simon.kelly@bbsrc.ac.uk or s.kelly@uea.ac.uk].
[†] University of East Anglia.
[§] Institute of Food Research.
[#] Food Standards Agency.

10.1021/jf0627726 CCC: $37.00

potential exists for fraud at many stages in these supply chains, particularly with regard to imported produce. The president of the International Organic Accreditation Service (IOAS) commented recently, "that there are few cases of fraud reported may be because they are not there or because the authorities do not look for them, or [they look] in the wrong places" (*6*). Siderer et al. comment that harmonization of methods, certification, and labeling is desirable if the organic market continues to increase and that analytical tests to help maintain the authenticity of products in the organic sector should be considered (*2*).

Synthetic nitrogen fertilizers, extensively used in conventional farming, are not permitted in organic agriculture. Soil fertility is maintained through the use of crop rotations that include legumes and green manures (plants grown to help maintain the structure and nutrient content of soil) and also by the application of certain naturally derived fertilizers. Synthetic nitrogen fertilizers tend to have stable nitrogen isotope values close to zero, usually between −2 and 2‰ (see, e.g., refs *7*−*10*). The nitrogen in these fertilizers is derived from atmospheric nitrogen ($\delta^{15}N_{atm} = 0$‰), and there is little fractionation during their manufacture. Fertilizers that may be permitted in organic farming include animal manures, composts, bloodmeal, fishmeal, hoof and horn, rapemeal, and seaweed-derived products. Manure is probably the most commonly applied source of nutrients in organic systems, and nitrogen isotope values between 10 and 20‰ are typically reported for manure-based fertilizers (*11*). Values for other fertilizers that may be permitted in organic regimens are not well documented but are likely to exhibit a wider range of compositions than synthetic fertilizers due to their more diverse origins.

Previous studies, principally pot experiments and field trials, have shown that the nitrogen isotope composition of an applied fertilizer influences the nitrogen isotope composition of the crop being grown (*12*−*14*). It has been suggested that such differences could be exploited to develop a method capable of distinguishing between conventionally grown crops and crops grown under organic conditions (*15*). However, there is evidence that the timing of application of a fertilizer (*16*) and the chemical form of a synthetic fertilizer (*17*) are important in determining how fertilizer δ^{15}N affects crop δ^{15}N. Additionally, there are many factors, other than fertilizer δ^{15}N value, that are likely to be influential over crop δ^{15}N values. These include soil type, antecedent land use, variability in atmospheric nitrogen deposition, variations in local agricultural practices, etc. For example, soil moisture levels were found by Choi et al. to be important in controlling the δ^{15}N of soil nitrate being produced from different fertilizer types (*15*).

In this study, we have collected and analyzed samples of commercially produced organic and conventionally grown tomatoes, lettuces, and carrots in order to assemble datasets that will make it possible to ascertain whether there are any systematic differences in the nitrogen isotope compositions of the organic and conventionally grown crops that could be exploited to detect fraud in the organic sector. Samples were obtained from many different growers from across a wide geographic area to ensure that the datasets contained crops grown in conditions with variability in the factors that may influence crop δ^{15}N, for both the organic and conventionally grown samples. Different growers will have used various types and amounts of fertilizer, and sowing time, harvest time, soil type, weather conditions, etc., will have been variable. Because there is no reason to expect that any of these factors, other than fertilizer type, is likely to be systematically different between organic and conventional growers, any differences in the nitrogen isotope compositions of the datasets are therefore likely to be attributable to the influence of fertilizer. We present the results from this study and also discuss their implications for using δ^{15}N analysis as a means of trying to detect deception when conventional produce is being sold as organic.

Table 1. Summary Statistics of the Nitrogen Isotope Data (δ^{15}N‰$_{(air)}$) for Commercially Produced Authentic Conventional and Organic Tomatoes, Lettuces, and Carrots

crop	production	n^a	mean	SD	min	max
tomato	conventional	46	−0.1	2.1	−4.2	5.3
	organic	61	8.1	3.2	0.2	16.6
lettuce	conventional	55	2.9	4.3	−3.0	17.3
	organic	49	7.6	4.1	0.8	17.2
carrot	conventional	17	4.1	2.6	1.0	9.1
	organic	13	5.7	3.5	0.7	11.2

[a] *n*, number of individuals analyzed; SD, standard deviation (σ^{n-1}); min, minimum value; max, maximum value.

MATERIALS AND METHODS

Collection of Samples. Establishing a database of authentic samples is one of the most important conditions if a stable isotope method is to be used as an officially acknowledged procedure for food quality control, and any database should take into account factors such as regional origin, plant species, variety, season, and climate (*18*). Organic samples were obtained either directly from certified organic growers, who were made aware of the aims of the project and had agreed to supply samples, or directly from organic farm shops selling their own produce. Although there is no absolute guarantee that all of the samples analyzed are genuine, we believe that this approach has minimized the chances of including in the datasets any conventional produce being fraudulently mis-sold as organic. The organic samples are dominated by samples from the United Kingdom (with a few EU samples) but are from a wide geographic spread encompassing a wide variety of soil types. Ideally, the conventionally grown produce would also have been obtained directly from farms with associated details of growing conditions and geographical origin. However, it was considered to be less important that these samples should be acquired directly from growers because there is no economic incentive to sell organically grown crops as conventional. Therefore, for pragmatic reasons, samples of conventional produce were obtained from a variety of local retail outlets, predominantly supermarkets. Care was taken to ensure that the conventionally grown produce came from many different geographical regions. Samples were predominantly grown within the United Kingdom and EU with a few samples from outside the EU. For both organic and conventional samples, many different varieties of each crop type were analyzed, and samples were collected and analyzed over a 2 year period (except for carrots, for which samples were only collected over a 1 year period, see below). The number of conventionally and organically grown samples of each crop type is shown in **Table 1**.

Analytical Procedures. Samples for nitrogen isotope analysis were freeze-dried, homogenized, and ground to a fine powder using a ball mill. Dried samples were weighed into tin capsules, and standards and samples were matched to give 0.1 mg (±20%) of N per analysis. The total N contents of standards and samples were closely matched to minimize errors associated with source-linearity effects. Nitrogen isotope compositions were determined using a PDZ Europa ANCA-GSL elemental analyzer connected to a 20:20 continuous flow isotope ratio mass spectrometer. Samples were analyzed in triplicate and values accepted when precision (σ^{n-1}, $n = 3$) was <0.3‰. Samples were referenced against a casein in-house standard with an accepted value of 6.3‰ (previously calibrated against International Atomic Energy Agency reference materials during an interlaboratory comparison exercise involving six European Food Control laboratories as part of EU Project SMT4-CT98-2236 to develop methods to determine the origin of milk, butter, and cheese). Long-term performance of the mass spectrometer was monitored by analysis of a secondary reference material, L-alanine, with an accepted δ^{15}N value of 8.7‰, in every batch. The long-term standard deviation of the values obtained from measurements of the secondary laboratory standard was 0.16‰. Nitrogen isotope data are reported in conventional δ notation in units of per mil (‰) with respect to atmospheric nitrogen (air) according to eq 1

$$\delta^{15}\mathrm{N}_{\mathrm{sample}}\ (‰) = \left(\frac{R_{\mathrm{sample}} - R_{\mathrm{standard}}}{R_{\mathrm{standard}}}\right) \times 1000 \qquad (1)$$

where $R = {}^{15}\mathrm{N}/{}^{14}\mathrm{N}$ and the standard is atmospheric nitrogen with a ${}^{15}\mathrm{N}/{}^{14}\mathrm{N}$ ratio of 0.00368 and a δ^{15}N value of 0‰.

Data Analysis. Using the mean and standard deviation values for the organic and conventional datasets, it is possible to generate the probability densities of the normal distribution curves for the expected entire populations of each group. The normal distribution is described by the equation

$$y = \frac{1}{\sigma\sqrt{2\pi}}\,\mathrm{e}^{-[(x-\mu)^2/2\sigma^2]} \qquad (2)$$

where y = frequency, $x = \delta^{15}$N value, σ = standard deviation, and μ = mean.

In our case, the mean of each group (organic/conventional) of the measured individuals ($\bar{x}$) can be used as an estimate of μ (the mean for each population), and the standard deviation of each dataset (σ^{n-1}) gives an estimate of σ for the population. The expected normal distributions of δ^{15}N values for the organic and conventional tomato populations have been constructed in this way using the NORMDIST function in Microsoft Excel, which produces a normal distribution for a specified mean and standard deviation. For a normal distribution, z scores of 1.96 and 2.58 are the limits on either side of a population mean, within which 95 and 99% of all observations will lie, where

$$z = \frac{x - \mu}{\sigma} \qquad (3)$$

where x = value of an individual observation, μ = mean of the entire population, σ = standard deviation of the entire population.

The values of μ and σ for the entire populations are not known, but $\bar{x}$ and σ^{n-1} can be used, respectively, as estimates from the datasets of measured values. To compensate for uncertainty in the estimates of μ and σ, the values of 1.96 and 2.58 must be increased, that is, set further out from the mean, and the symbol z is replaced by t. t distributions are determined not only by the mean and standard deviation but also by sample size (i.e., the number of observations). Critical t scores can be found in standard statistical tables (e.g., ref *19*). The t score for an observation x can be calculated using eq 4

$$t = \frac{x - \bar{x}}{\sigma^{n-1}} \qquad (4)$$

where x = value of an individual observation (e.g., the δ^{15}N value of a tomato), $\bar{x}$ = mean of the sample set, and σ^{n-1} = standard deviation of the sample set.

For an observation with a particular δ^{15}N value (x), if the calculated value of t is larger than that tabulated for ($n - 1$) degrees of freedom at $p = 0.05$, it can be concluded that the observation is "unlikely" to have been drawn from a population with the same mean and standard deviation as the baseline dataset (either the organic or conventional dataset). If the calculated value of t is larger than that tabulated for ($n - 1$) degrees of freedom at $p = 0.01$, then it can be concluded that the observation is "highly unlikely" to have been drawn from a population with the same mean as that from which the sample was drawn (*19*). As an example, shown in **Table 2** are the critical t values based on the number of organic and conventional tomatoes in the gathered datasets—obtained by interpolation between the values given in standard statistical tables. Each t value in **Table 2** can be substituted into eq 4, and the corresponding $\bar{x}$ and σ^{n-1} values input to find the values of x (value of δ^{15}N) within which 95 and 99% of all the observations are expected to lie.

Table 2. Critical *t* values for the Organic and Conventional Tomato Datasets

	n^a	degrees of freedom ($n-1$)	critical t value at $p = 0.05$	critical t value at $p = 0.01$
conventional	46	45	2.016	2.693
organic	61	60	2.000	2.660

[a] *n*, number of individuals.

RESULTS AND DISCUSSION

Tomatoes. The mean nitrogen isotope value for the organically grown tomatoes is 8.2‰ higher than the mean value for the conventionally grown tomatoes (**Table 1**). Although there is a definite tendency for organically grown tomatoes to have higher nitrogen isotope values, there is overlap between the nitrogen isotope values for the organically and conventionally grown tomatoes between 0 and 6‰ (**Figure 1a**). This means that the classification of tomatoes of unknown production origin as organic/conventional when they lie within or close to this range is subject to considerable uncertainty. The approach described under Data Analysis was used to quantify the level of uncertainty.

Modeled normal distribution curves for the organic and conventional tomato populations are shown in **Figure 2**. Ninety-five percent ($p = 0.05$) of the modeled organic population would be expected to have stable nitrogen isotope values between 1.7‰ and 14.4‰. Of the remaining 5% of the population, 2.5% would be expected to fall in each of the distribution tails. This means that 5 of 200 organic samples could be expected to have δ^{15}N values of <1.7‰. A tomato with a δ^{15}N value of <1.7‰ can be described as statistically unlikely to be drawn from a population with the same mean as the set of organic tomatoes analyzed during the baseline survey. In the same way, it can be said that a tomato with a δ^{15}N value of <-0.5 is statistically highly unlikely to be drawn from a population with the same mean as the organic dataset analyzed during the baseline survey. In this case, 0.5% of the entire modeled population would be expected to fall in each of the distribution tails ($p = 0.01$); that is, 1 of 200 organic samples would be expected to have a δ^{15}N value of <-0.5‰.

Figure 2 also shows that just <50% of conventionally grown tomatoes would be expected to have δ^{15}N values of <-0.5‰. This is important when considering whether δ^{15}N values could be useful in the discrimination between organically and conventionally grown tomatoes because to be able to detect any fraudulent substitution of conventional produce for organic, the conventional produce must have a nitrogen isotope signature that is distinct from that of the organic produce. Also worthy of note is that the use and interpretation of the data as described above assume that the datasets used (i.e., the organic and conventional tomatoes collected and analyzed) are representative of their corresponding entire populations, that is, that these subsets of the populations are unbiased in any way. In fact, they do contain bias. The organic samples were dominated by tomatoes grown in the United Kingdom, so this subset is not a random subset of the entire organic tomato population. There is greater diversity in the origin of the conventionally grown tomatoes with samples from the United Kingdom, Spain, Holland, and Italy. In reality, both organic and conventional tomatoes could be grown anywhere in the world. Having recognized that the datasets are not random samples from their

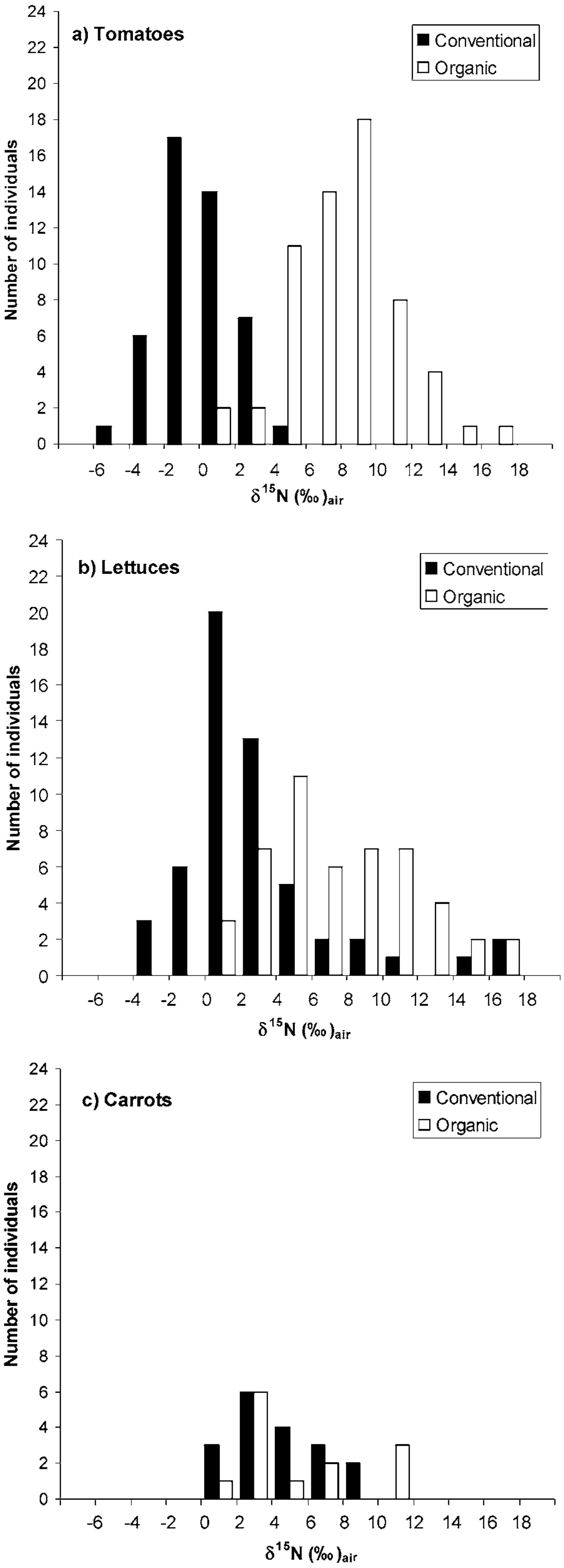

Figure 1. Histograms showing the δ^{15}N‰$_{(air)}$ values of organic and conventional crops: (**a**) tomatoes; (**b**) lettuces; (**c**) carrots.

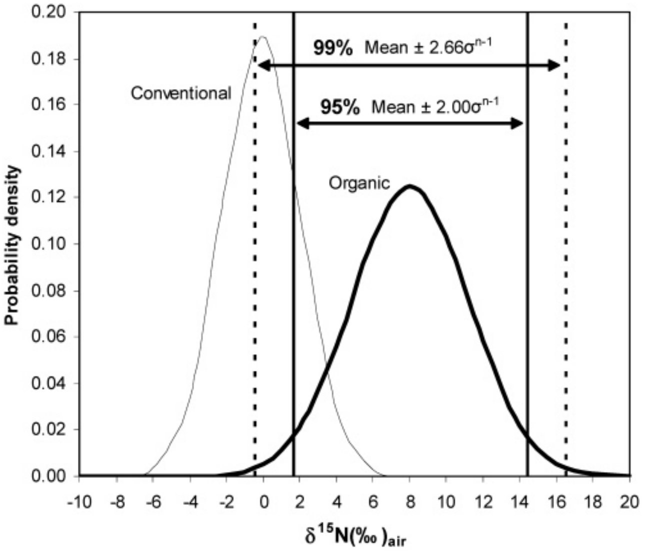

Figure 2. Modeled normal distribution curves for the organic (bold curve) and conventional (fine curve) tomato populations. The solid and dashed lines show the limits between which 95 and 99% of the organic population would be expected to fall, based on the mean and standard deviation of the measured dataset and assuming that the measured dataset is representative of the whole organic population (see text for further details).

respective populations, it is worth considering what the implications of this might be. There are two main systems of tomato production in the EU. In the United Kingdom, Holland, Belgium, Denmark, and Germany, tomatoes are principally produced in greenhouses in soil-less conditions on substrates such as rockwool and fed continuously with a nutrient solution (*20*). In these northern countries, most tomatoes are grown for the fresh market. In Mediterranean countries, tomatoes are typically grown in the soil usually outside and less commonly in greenhouses. Four Mediterranean countries (Greece, Italy, Portugal, and Spain) produce 15 billion kilograms of tomatoes on 236 000 ha with a value of Euro 8.7 billion/year. Approximately 35% of the tomatoes grown in these four Mediterranean countries are marketed fresh, whilst the remainder are processed (*20*).

Sixty-three percent of the conventional tomato samples analyzed in the baseline survey were sourced from the United Kingdom and Holland, with 33% from Mediterranean countries (the country of origin of the remaining samples was unknown). The conventional samples are therefore a mixture of tomatoes likely to have been grown in the soil-less conditions favored by the northern European countries and Mediterranean soil-grown tomatoes. However, no significant difference was found between the δ^{15}N values for the samples sourced from Mediterranean countries and the values for those from the northern European countries (*t* test, $p = 0.063$).

All except four of the organic tomato samples were grown in the United Kingdom, and this clearly represents a bias in the dataset. Other than the type of fertilizer applied, we have already mentioned other variables that could potentially affect the nitrogen isotope composition of crops, for example, soil type, weather/climate conditions, and agricultural management practices. The tomatoes from across the United Kingdom have been grown in soils with descriptions ranging from stony brown earth and peaty loam to sandy and clay soils. Geographically, the tomatoes have been grown in locations from North Yorkshire to West Sussex. Although this sampling includes a considerable variety in soil type, the range in weather/climate conditions is relatively narrow compared to the climates of some of the countries from which the United Kingdom commonly imports organic tomatoes (e.g., Spain and Italy). Few samples from a wider geographical spread (outside the United Kingdom) were analyzed because of the difficulty in obtaining samples direct from growers (considered to be necessary to prevent the possibility of analyzing produce that had been mislabeled during transit along multistep supply chains). Increasing the number of non-U.K.-sourced tomatoes in the organic tomato dataset would considerably improve the integrity of the organic tomato database.

All of the organic tomatoes analyzed in this survey were grown in soil. Growing organically and growing hydroponically are traditionally viewed as being mutually exclusive, and the principles of organic growing are not easily applied to hydroponic growing. Lammerts van Bueren et al. (*21*) comment that the growing of plants in completely artificial environments violates what they term the concept of "plant-specific integrity". Plant-specific integrity is defined as the state of wholeness or completeness of a plant and its ability to perform all of its plant-specific functions. They conclude that hydroponic culture does not "correspond to [a] plant's worthiness in the organic sense". The IFOAM Norms for organic production and processing state that "organic growing systems are soil based" and that "organic plant breeding is a holistic approach that respects natural crossing barriers and is based on fertile plants that can establish a viable relationship with the living soil" (*1*).

Lettuces. The summary statistics show that there is a tendency for conventionally grown lettuces to have δ^{15}N values lower than those grown organically (**Table 1**). However, there is more overlap between the δ^{15}N values of the organic and conventionally grown lettuces compared to the tomatoes (**Figure 1b**). One main difference is that there are a number of conventional lettuces that have δ^{15}N values between 8 and 18‰ whereas none of the conventionally grown tomatoes had a δ^{15}N value of >5.3‰. This suggests that the stable nitrogen isotope compositions of these lettuces are apparently uninfluenced by synthetic nitrogen fertilizers, and there are a number of possible explanations for why this may be the case. First, a conventional grower may quite legitimately choose not to use a synthetic nitrogen fertilizer and may instead use any of the fertilizers that may be permitted in organic systems. Second, if supply of organic crops exceeds demand, then it is possible that an organic grower may not be able to find an outlet for the organically grown crop and may end up selling his crop through conventional channels at conventional prices. This was certainly the case at one point in the dairy sector when oversupply of the organic milk market led to only 46% of milk produced organically being sold as organic, with the surplus being sold as conventional (*22*). Another possible explanation is that during a period of conversion from conventional to organic, growers are not allowed to use synthetic fertilizers. In these circumstances, a grower cannot sell his produce as organic until the end of the conversion period, so during this time the produce would be sold as conventional but may have a δ^{15}N signature typical of a crop grown without using synthetic nitrogen fertilizer. Finally, the conventionally grown lettuces may be more widely spread in terms of their δ^{15}N values compared to tomatoes due to differences in the way they are cultivated. Nearly all commercially grown conventional tomatoes in the United Kingdom are grown in protected conditions, and they are dominantly hydroponically grown. The horticultural statistics for 2003 produced by the Department for Environment Food and Rural Affairs show that lettuces grown in the United Kingdom under protected conditions have a market value of £19 million (*23*). This compares with an estimated market value of £74 million for field-grown lettuces (*23*). This means that compared to tomatoes, a much larger proportion of the conventional lettuces analyzed are likely to have been grown in soil. Under hydroponic conditions, there is little opportunity for nitrogen cycle processes to affect the δ^{15}N composition of the nutrient solution that is circulated through the soil-less growing medium. There is much greater potential for the nitrogen isotope composition of field-grown crops to be affected by variables other than the δ^{15}N of the applied fertilizer. For example, there will be soil-derived nitrate present in the system, leaching of applied fertilizers may occur, and there may be an additional source of nitrogen from both dry and wet deposition of atmospheric nitrogen.

The lettuce data could be treated in the same way as described above for the organic and conventional tomato data, although some allowance would need to be made for the non-normally distributed data (the tail in the conventional dataset). However, it is pre-evident that a large number of conventionally grown lettuces have δ^{15}N values that overlap with the δ^{15}N values of organically grown lettuces. In part, this exposes a shortcoming of the conceptual approach taken so far in treating the organic and conventionally grown datasets as two separate sets that have an "intersection" (with respect to classic set theory) in terms of their δ^{15}N values. With regard to the tomato datasets, this approach apparently describes the measured nitrogen isotope data reasonably well with two normally distributed datasets with a region of overlap. However, as pointed out above, a conventional grower may use a synthetic nitrogen fertilizer or choose to use any of the fertilizers that may be permitted in organic systems. It is only organic growers who are restricted in the fertilizers that they may use. In terms of classic set theory, the fertilizers that may be applied by organic growers are a "subset" of the fertilizers available to conventional growers, and therefore it might be expected that the range of nitrogen isotope values for organically grown produce is also a subset of the observed range for conventionally grown produce (although this is theoretically also the case for the tomatoes, in reality, it is apparent that conventional tomato growers probably tend to use predominantly synthetic nitrogen fertilizers). However, the subset conceptual approach seems to better describe the observed organic and conventional lettuce datasets.

In our baseline survey, the minimum nitrogen isotope value recorded for an organically grown lettuce was 0.8‰. Around 30% of the conventionally grown lettuces had a δ^{15}N value below this. The organic lettuce dataset is normally distributed and, in a similar manner as described for the tomato data, the mean, standard deviation, and appropriate t value from statistical tables can be used to calculate that 95% of the entire organic lettuce population can be expected to fall between −0.1 and 16.4‰. This means that we can expect 5 of 200 organic lettuces to have δ^{15}N values below −0.1‰. A lettuce with a δ^{15}N value of <−0.1‰ can be described as statistically unlikely to be from a population with the same mean and standard deviation as the set of organic lettuces analyzed during the baseline survey. This information is of less practical use than that for the tomatoes because, as stated earlier, to be able to detect any fraudulent substitution of conventional produce for organic, the conventional produce must have a nitrogen isotope signature that is distinct from that of the organic produce. The much greater overlap between the nitrogen isotope signatures of the organic and conventionally grown lettuce datasets means that only a moderately small proportion of conventionally grown samples would be expected to have δ^{15}N values of <−0.1‰.

Carrots. There is almost complete overlap between the stable nitrogen isotope compositions of the organically and conventionally grown carrots (**Figure 1c**). A t test confirms that there is no significant difference between the mean values for the two groups ($p = 0.169$). The dataset of carrot samples is relatively small, and this is because collection of samples was discontinued because these preliminary data suggest that nitrogen isotope composition is not useful in trying to discriminate between carrots grown organically and those grown conventionally.

A possible explanation why there is no apparent difference in the nitrogen isotope compositions of the organic and conventional carrots, whereas differences were observed for tomatoes and lettuces, may be the lower nitrogen requirement of carrots. Lettuces and tomatoes have a medium nitrogen requirement compared to carrots, which have a low nitrogen requirement (*24*). Other differences between the cultivation of carrots and lettuces/tomatoes include (i) propagation of lettuces/tomatoes in blocks or modules before planting out and the fertilizers that may be applied during this propagation stage and (ii) the fact that in an organic rotation system, it is advisable to avoid planting of carrots soon after the application of farmyard manure as this increases the likelihood of mis-shapen roots (*25*).

Wider Discussion. The results from the baseline survey suggest that crop δ^{15}N values will be a better indicator of whether crops have been grown with/without synthetic fertilizers for some crop types than others. In this survey, because the conventionally grown crops were obtained from retail sources, we do not know the cultivation conditions for these samples. We have not therefore established conclusively the explanation for why we see a difference in the δ^{15}N values of conventionally and organically tomatoes and lettuces but do not see a difference for carrots. We hypothesize that it may be because of the lower nitrogen requirements of carrots and consequently generally lower levels of fertilizer application or because carrots are field-grown crops whereas tomatoes and lettuces are often grown under protected conditions and usually fertilized many times (or continuously in hydroponic systems) during the growth period. Most likely it is a combination of these factors, the timing/amount of fertilizer application and the fact that it is easier to ensure that fertilizer is targeted directly at plants in the conditions (hydroponic/protected) in which tomatoes and, to a lesser extent, lettuces are grown, compared to field-grown crops such as carrots, for which other sources of nitrogen and nitrogen-cycling processes may have a much larger influence on crop δ^{15}N values. The apparent unsuitability of nitrogen isotope data for discriminating between organically and conventionally produced field-grown crops such as carrots, with a relatively low nitrogen requirement, is in agreement with the results of a study by Schmidt et al. (*26*). Whereas Schmidt et al. (*26*) found significant differences between the δ^{15}N values of greenhouse-grown organic and conventional paprika and tomatoes, no significant differences were found between the nitrogen isotope values of organically and conventionally cultivated wheat grown at a number of locations throughout southeastern Germany.

The statistical analyses of the results show the manner in which this type of data might be used. The type of statement that could be made is “it is *unlikely* or *highly unlikely* that a tomato with this nitrogen isotope composition would have been grown without the use of synthetic nitrogen fertilizers”. Assessments of test samples (of unknown origin and unknown growing conditions, organic/conventional) can be made by comparison with a database of authentic samples. Simpkins and Harrison (*27*) comment that “Trade in foodstuffs is global so there is a need for data on authentic products from many different parts of the world. The exchange of reliable database information should increase...”. Similarly, Rossman (*18*) asserts that “the establishment of a relevant database for statistical evaluation...should take into considerations important factors, e.g., regional origin, plant species, variety, season and climate”. From this perspective there is a limitation in the datasets presented here because they are dominated by samples of U.K. origin with a few EU samples. Rossman (*18*) goes on to say that “[a] second prerequisite is that a sufficient number of laboratories are able to apply the method with good accuracy and precision”. This is one of the strengths of the nitrogen isotope approach. Preparation of samples and the nitrogen isotope analysis is relatively straightforward and inexpensive, suitable for daily routine processing with a high throughput of samples. The accuracy and precision of samples analyzed for their nitrogen isotope composition is routinely monitored in stable isotope laboratories using widely available International Atomic Energy Agency (IAEA) standards. Extending the authentic databases to include samples from a wider geographical spread would therefore be straightforward.

Table 3. Possible Outcomes When a Stable Isotope Endproduct Test Is Applied to a Sample

			REALITY	
			Has a synthetic fertilizer been used?	
			Yes	**No**
STABLE ISOTOPE TEST	**Has a synthetic fertilizer been used?**	**Yes**	Test gives the correct result	Test gives a false positive
		No	Test gives a false negative	Test gives the correct result

Another consideration is that there may be a transition over time from the current situation in which conventional farming methods tend to be relatively high input and intensive, favoring maximization of crop yields, toward more sustainable methods in which economic profitability but also environmental health and social and economic equity become increasingly important goals. A move toward more sustainable lower input conventional agricultural systems may include reducing synthetic nitrogen inputs, and this might reduce differences between the nitrogen isotope compositions of organic and conventionally grown crops. Databases of authentic samples would need to be maintained to reflect any changes in agricultural practices over time, and the cost of this should be taken into account when it is considered whether the nitrogen isotope approach is worth pursuing.

A consideration when using an endproduct test such as the nitrogen isotope approach is what the consequences might be if the test is not 100% accurate. **Table 3** shows the possible outcomes from applying a stable isotope test. Ideally, the test would always correctly determine whether a crop has been grown with or without the use of synthetic fertilizers. In **Table 3**, this is where the answer to the question, “has a synthetic fertilizer been used?” is the same in “reality” and as indicated by the “stable isotope test”. However, there are two other possible outcomes, both of which are undesirable. First, there is the issue of false negatives. In this situation, the stable isotope test would indicate that synthetic fertilizer had not been used on a crop being sold as organic when, in reality, it had. This would mean that the test would not detect fraud when in fact it was taking place. With a test balanced in favor of false negatives, there is the danger of unwarranted complacency that there is no fraud taking place. More serious is the issue of false positives. In this situation, the stable isotope test would indicate that a synthetic fertilizer had been used when in fact it had not. This interpretation could lead to false accusations against legitimate producers, wholesalers, or packing houses, with the potential to undermine trust in the organic sector.

Nitrogen isotope analysis provides only information as to whether synthetic nitrogen fertilizers have been applied to a crop and cannot, therefore, be described as one that would allow the authenticity of an organic crop to be assured. This is because the restriction on the use of synthetic nitrogen fertilizers is only one of a range of conditions that must be met to satisfy the requirements of organic farming. Additional obligatory conditions are a period of conversion and registration with an appropriate certifying authority, which clearly cannot be ascertained from nitrogen isotope measurements. The technique described here has the potential to detect conventional produce grown using synthetic fertilizers that is fraudulently on sale as organic but not to verify all aspects of the authenticity of organic crops.

Conclusions. The baseline survey results demonstrate that the nitrogen isotope approach is capable of providing intelligence on whether synthetic nitrogen fertilizers are likely to have been applied to certain crop types. A δ^{15}N analysis on a test sample would not provide unequivocal evidence as to whether synthetic fertilizers have been used on the crop but could, for example, in a situation when there is suspicion that mislabeling of conventionally grown crops as organic is occurring, be used to provide supporting evidence.

We strongly advocate that endproduct tests such as the nitrogen isotope approach cannot and should not be thought of as a replacement for organic certification and inspection schemes and that interpretation of analyses should be made carefully and sensitively. However, it is our view that any analytical techniques that assist in protecting consumers from fraud and help to protect the interests of all honest growers and traders should be viewed positively.

LITERATURE CITED

(1) International Federation of Organic Agriculture Movements. *The IFOAM Norms for Organic Production and Processing*, version 2005; 2006, IFOAM: Bonn, Germany, 2006; 126 pp.

(2) Siderer, Y.; Maquet, A.; Anklam, E. Need for research to support consumer confidence in the growing organic market. *Trends Food Sci. Technol.* **2005**, *16*, 332−343.

(3) Council Regulation (EEC) 2092/91. *Organic Production of Agricultural Products and Indications Referring Thereto on Agricultural Products and Foodstuffs*; Office for Official Publications of the European Communities, CONSLEG: Brussels, Belgium, 2004; 94 pp.

(4) Willer, H.; Yussefi, M. *The World of Organic Agriculture. Statistics and Emerging Trends*, 8th ed.; International Federation of Organic Agriculture Movements (IFOAM): Bonn, Germany; Research Institute of Organic Agriculture FiBL: Frick, Switzerland, 2006; 196 pp.

(5) Raynolds, L. T. The globalization of organic agro-food networks. *World Dev.* **2003**, *32*, 725−743.

(6) van Elzakker, B.; Neuendorff, J. Abstract for report on the EU regulation and organic integrity: needs and recommendations for control measures and certification, 2005, organic hazard analysis and critical control points; available at http://www.organichaccp.org/RepSum8.asp.

(7) Kohl, D. H.; Shearer, G. B.; Commoner, B. Fertilizer nitrogen: contribution to nitrate in surface water in a corn belt watershed. *Science* **1971**, *174*, 1331−1334.

(8) Shearer, G. B.; Kohl, D. H.; Commoner, B. The precision of determinations of the natural abundance of nitrogen-15 in soils, fertilizers and shelf chemicals. *Soil Sci.* **1974**, *118*, 308−316.

(9) Zielinski, R. A.; Asher-Bolinder, S.; Meier, A. L.; Johnson, C. A.; Szabo, B. J. Natural or fertilizer-derived uranium in irrigation drainage: a case study in southeastern Colorado, U.S.A. *Appl. Geochem.* **1997**, *12*, 9−21.

(10) Vitoria, L.; Otero, N.; Soler, A.; Canals, A. Fertilizer characterization: isotopic data (N, S, O, C, and Sr). *Environ. Sci. Technol.* **2004**, *38*, 3254−3262.

(11) Bedard-Haughn, A.; van Groenigen, J. W.; van Kessel, C. Tracing ^{15}N through landscapes: potential uses and precautions. *J. Hydrol.* **2003**, *272*, 175−190.

(12) Yoneyama, T.; Kouno, K.; Yazaki, J. Variation of natural ^{15}N abundance of crops and soils in Japan with special reference to the effect of soil conditions and fertilizer application. *J. Soil Sci. Plant Nutr.* **1990**, *36*, 667−675.

(13) Nakano, A.; Uehara, Y.; Yamauchi, A. Effect of organic and inorganic fertigation on yields, δ^{15}N values, and δ^{13}C values of tomato (*Lycopersicon esculentum* Mill. cv. Saturn). *Plant Soil* **2003**, *255*, 343−349.

(14) Bateman, A. S.; Kelly, S. D.; Jickells, T. D. Nitrogen isotope relationships between crops and fertilizer: implications for using nitrogen isotope analysis as an indicator of agricultural regime. *J. Agric. Food Chem.* **2005**, *53*, 5760−5765.

(15) Choi, W. J.; Ro, H. M.; Lee, S. M. Natural ^{15}N abundances of inorganic nitrogen in soil treated with fertilizer and compost under changing soil moisture regimes. *Soil Biol. Biochem.* **2003**, *35*, 1289−1298.

(16) Choi, W. J.; Lee, S. M.; Ro, H. M.; Kim, K. C.; Yoo, S. H. Natural ^{15}N abundances of maize and soil amended with urea and composted pig manure. *Plant Soil* **2002**, *245*, 223−232.

(17) Evans, R. D.; Bloom, A. J.; Sukrapanna, S. S.; Ehleringer, J. R. Nitrogen isotope composition of tomato (*Lycopersicon esculentum* Mill. cv. T-5) grown under ammonium or nitrate nutrition. *Plant, Cell Environ.* **1996**, *19*, 1317−1323.

(18) Rossman, A. Determination of stable isotope ratios in food analysis. *Food Rev. Int.* **2001**, *17*, 347−381.

(19) Fowler, J.; Cohen, L. *Practical Statistics for Field Biology*; Wiley: New York, 1992; 227 pp.

(20) Gianessi, L.; Sankula, S.; Reigner, N. *Tomato-Virus Resistant Case Study, Plant Biotechnology: Potential Impact for Improving Pest Management in European Agriculture*; The National Center for Food and Agricultural Policy: Washington, DC, 2003.

(21) Lammerts van Bueren, E. T.; Struik, P. C.; Tiemens-Hulscher, M.; Jacobsen, E. Concepts of intrinsic value and integrity of plants in organic plant breeding and propagation. *Crop Sci.* **2003**, *43*, 1922−1929.

(22) Ritchie, C. A.; Middleton, J.; Smith, N. L. *A. Guide to the Marketing of Organic Food*; Scottish Agricultural College: Aberdeen, Scotland, 2000.

(23) Department for Environment, Food and Rural Affairs. Basic Horticultural Statistics, 2004; available at http://statistics.defra.gov.uk/esg/publications/bhs.

(24) Ministry of Agriculture, Fisheries and Food. *Fertilizer Recommendations for Agricultural and Horticultural Crops (RB209)*; The Stationery Office: London, U.K., 2000.

(25) Soil Association. *Organic Carrot Production*; Soil Association: Bristol, U.K., 1999.

(26) Schmidt, H.; Rossman, A.; Voerkelius, S.; Schnitzler, W. H.; Georgi, M.; GraBmann, J.; Zimmermann, G.; Winkler, R. Isotope characteristics of vegetables and wheat from conventional and organic production. *Isotopes Environ. Health Stud.* **2005**, *41*, 223−228.

(27) Simpkins, W.; Harrison, M. The state of the art in authenticity testing. *Trends Food Sci. Technol.* **1995**, *6*, 321−328.

Received for review September 27, 2006. Revised manuscript received January 8, 2007. Accepted January 25, 2007. This work was financed by the U.K. Food Standards Agency as part of its Food Authenticity and Labelling Programme, Project Q01076. The views expressed in this paper are those of the authors and do not necessarily reflect the views of the U.K. Food Standards Agency.

JF0627726