Chapter 5

Nutrient Supply in Organic Agriculture – Plant Availability, Sources and Recycling

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Abstract This chapter examines the practice of applying nutrients in organic or slowly soluble inorganic form in the belief that plants will obtain balanced nutrition through the actions of soil microbes. The organic principle of only fertilising the soil and not directly feeding the crop with water-soluble nutrients has no support in science. The release of organically bound nutrients in soil through biological activity is not necessarily synchronised with crop demands and occurs even at times when there is no crop growth. Changes in the soil biological community do not overcome this limitation. Despite the ideal of organic agriculture being self-sustaining through cycling of nutrients, in principle only on-farm wastes are recycled and most municipal wastes are excluded due to concerns about pollutants and philosophical views on life (biodynamic agriculture). Nutrient supply in European organic agriculture is mainly covered through purchase of straw, manure and fodder from conventional agriculture and by-products from the food industry. Untreated minerals seem to play a minor role. The fertility of agricultural soils can only be maintained over the long-term if plant nutrients removed, are replaced with equivalent amounts and if added sources have a higher solubility than those present in the soil. These conditions are in most cases not fulfilled in organic agriculture. It can thus be concluded that the naturalness of nutrient sources is no guarantee of superior quality and that promotion of organic principles does not improve the supply and recycling of nutrients but excludes other more effective solutions for nutrient use in agricultural systems.

Keywords Nitrogen input · Soil fertility · Crop yield · Waste recycling · Rock phosphate · Nitrate leaching · Nutrient recycling · Organic manures · Fertilisers

1. INTRODUCTION

Use of plant nutrients in organic agriculture is viewed differently than in conventional agriculture. Nutrients are supplied in organic forms or as untreated minerals with low solubility in the belief that plants will obtain balanced nutrition through the actions of roots and soil microbes and through weathering of minerals. The premise of organic agriculture is to supply the soil with nutrients but not directly feed the plants with soluble nutrients. Organic agriculture was founded on the dogma, as opposed to the hypothesis, that the use of organically bound nutrients and untreated minerals is superior to the use of artificial fertilisers, which are classified as being unnatural. Therefore, all fertilisation practices are designed and characterised according to this dogma (Watson et al., 2002a). Over time, this has led to the common opinion that the exclusion of soluble inorganic fertilisers contributes towards increased soil fertility and conservation of resources, and is a sound form of nutrient management. However, the most central question is whether the exclusion of artificial fertilisers can be justified scientifically. Is the naturalness of organic manures and untreated minerals associated with superior characteristics and functioning? Another idea central in organic agriculture is to view farms as sustainable units based on nutrient recycling and use of local resources.

In this chapter, we study the literature to determine whether and how the data reject or strengthen the arguments for abolishing soluble inorganic fertilisers in organic crop production. The question of self-sufficiency of farms is also examined. As organic principles have been adopted in many types of agricultural systems with vastly different soils and as social and political pressure increases for an even more widespread adoption of organic agriculture across the globe, the exclusion of inorganic fertilisers requires an in-depth examination.

Central aspects reviewed in this chapter are:

- The basis for exclusion of soluble inorganic fertilisers;
- Problems relating to reliance on organic nutrient sources and untreated minerals;
- The potential to recycle nutrients and thus the sustainability of organic production systems.

2. THE ORGANIC PRINCIPLE - TO FERTILISE THE SOIL AND NOT FEED THE CROP WITH ARTIFICIAL FERTILISERS

2.1. The humus theory and plant nutrients

The founders of organic agriculture regarded a living soil and the release of nutrients through soil biological activity as the proper way to supply crop demands. Addition of artificial, water-soluble fertilisers was deemed an unnatural way of plant nutrition. During the search for plant nutrients through history from Aristotle (384-322 BC) to Thaer (1752-1828 AD), the prevailing view was that organic manures such as animal wastes, composts, etc. increase soil fertility and that soil humus is the source of plant growth. Thaer (1837-1839) viewed humus as the residues of animal and plant putrefaction, a black body that formed the source for plant dry matter (Feller et al., 2003). Later, von Liebig (1840) added new, substantiated knowledge to this standpoint by showing that plants take up nutrients in the form of dissolved salts. Von Liebig introduced the 'Law of the Minimum', meaning that crops require a minimum of mineral substances for growth. Von Liebig (1840) wrote that '*even to great leaders in plant physiology, carbonic acid, ammonia, acids and bases are sounds without meaning, words without sense, terms of an unknown language, which awake no thoughts and no associations*'. Von Liebig proved that humus is not taken up by crops as such but is a source of plant nutrients released in water-soluble form. He provided the missing knowledge for understanding how humus acts in soil, and thereby corrected and complemented the humus theory with a mechanistic explanation. He showed that independent of origin, a number of essential elements dissolved in the soil solution act as plant nutrients, and this concept forms the basis for modern plant nutrition.

Relating the findings of von Liebig to the organic principle of excluding artificial, water-soluble fertilisers raises some central questions. Is addition of completely water-soluble nutrient sources to plants an unnatural practice? Are artificial fertilisers the only compounds containing water-soluble nutrients or are the organic materials used in organic agriculture also a significant source? Are the amounts of water-soluble nutrients added through artificial and organic fertilisers highly different? Is nutrient addition through artificial fertilisers poorly adjusted to the uptake dynamics of crops?

2.2. Water solubility of nutrients supplied with organic fertilisers and untreated minerals

Artificial fertilisers are excluded in organic agriculture, primarily due their function of directly feeding the crop, which is the result of their high or complete solubility in water. However, a closer examination of natural products used in organic agriculture reveals that these products can also be highly water-soluble (see Table 1). For example, urine contains more than 94% of its nitrogen as soluble ammonium/ammonia (e.g. Kirchmann and Pettersson, 1995) and animal slurries contain 50 to 70% of total N as ammonium (e.g. Bernal et al., 1993). Ulén (1984) found that up to one-third of the P content from clover/grass leys was released upon freezing. The vacuole of each mature plant cell contains most of the plant potassium, phosphate, calcium and magnesium, which are released upon freezing or mechanical destruction of the plant. Ploughing under of green manure crops also provides substantial amounts of soluble minerals to the soil. The release of P and K from fresh, barley straw has been shown to amount to 60 and 90%, respectively, of its total content upon cold-water leaching (Christensen, 1985), with inorganic ions being the main form. Moreover, a number of natural minerals approved for organic agriculture are highly water-soluble, e.g. halite (NaCl), kieserite ($MgSO_4$ x 2 H_2O), crude potassium salts e.g. kainit (($KMg(ClSO_4)_4$ x 11 H_2O), and ash containing e.g. potash (K_2CO_3). In contrast, even artificial fertilisers may not be completely water-soluble, for example di-ammonium phosphate of fertiliser grade quality contains 5-20% water-insoluble phosphates (Gilkes and Mangano, 1983; Nielsson, 1987).

Concerning the amount of soluble nutrients added, application of 30 Mg cattle slurry containing 2.0 kg NH_4-N Mg^{-1} provides, for example, 60 kg N ha^{-1}, while 40 Mg urine containing 1.7 kg NH_4-N Mg^{-1} adds 68 kg N ha^{-1}, which are close to the amounts usually applied with inorganic fertiliser. In addition, urine does not add any significant amount of organic material as it is a solution of excreted salts.

Soluble ions are provided to the soil not only through application of agricultural fertilisers, but also as atmospheric deposition of different compounds. For example, deposition of sea salt spray is a significant source of fully soluble sodium, chloride, calcium, etc. Annual fluxes of marine aerosols through deposition can amount to 51 kg of chloride and 25 kg of sodium per hectare in southern Sweden (Hultberg and Grennfeldt, 1992). Ammonia, which is mainly emitted from livestock (ECETOC, 1994) and which is highly water-soluble, is deposited both close to and far from the source and can add tens of kilograms of fully soluble nitrogen to soil (Ferm, 1998). However, the most obvious example of high natural salt concentrations in soil is through high evaporation under arid climatic conditions, where soluble ions from deeper layers are transported through mass flow to the soil surface, where they form saline, saline-sodic or sodic soils in which high salt concentrations actually stress crop growth (Brady and Weil, 2008). The high calcium concentrations in the soil solution of calcareous soils, in excess of crop demand, show that large amounts of soluble ions in the soil solution are in no way an abnormal condition for plants.

Table 1. Water-solubility of organic materials, wastes and minerals approved for organic agriculture

Type of material and nutrient	Water-soluble portion (%)	Reference
Organic wastes		
Animal slurry–N	50-70	Bernal et al. (1993)
Animal dung-N (anaerobic storage)	51-75	Kirchmann and Witter (1992)
Urine–N	94	Kirchmann and Pettersson (1995)
Green manures and crop residues		
Clover/grass foliage-P	11-33	Ulén (1984)
White clover foliage-N	36-41	Kirchmann and Bergqvist (1989)
Potato haulm-N	35	Henriksen and Breland (1999)
Barley straw-N	33-58	Reinertsen et al. (1984)
Barley straw-P	60	Christensen (1985)
Barley straw-K	90	Christensen (1985)
Industrial wastes		
Vinasse-K	100	PDA (2008)
Untreated minerals		
Kieserite–Mg and S	100	Härdter et al. (2004)
Kainit-K	100	Ullmann's Agrochemicals (2007)
Halite-Cl	100	Lide (1999)
Copper sulphate-Cu[a]	100	Lide (1999)

[a] Although the EU theoretically banned copper sulphate in 2002, the compound can still be used as a fungicide in organic agriculture as no alternative has been presented.

2.3. Dynamics of nutrient release from organic matter in soil

Inorganic ions present in or released from organic fertilisers are identical to ions released from artificial fertilisers. Nutrient uptake by crops is mainly through inorganic ions, with organic nutrient uptake being of minor importance (see Chapter 10 of this book; Ryan and Tibbett, 2008). As plant roots do not distinguish between solutes due to origin, except for possible discrimination against heavier isotopes, ions derived from artificial fertilisers or natural materials are involved in the same processes in the soil and in the crop. In other words, a molecule, for example, ammonium in slurry or in nitrogen fertiliser, undergoes the same reactions in soil since the chemical properties of a molecule are not affected by its origin. However, despite identical characteristics of soluble nutrients derived from organic manures, untreated minerals or artificial fertilisers, a sophisticated argument against artificial fertilisers has been presented by the founder of organic-biological agriculture (Rusch, 1978). Rusch pointed out that the dynamic release of nutrients from soil organic matter and the availability of nutrients over time is the main difference. Artificial fertilisers cause a high initial nutrient concentration in soil solution upon addition, whereas Rusch (1978) assumed that there is synchrony regarding the release of nutrients from soil organic matter and the demand of growing crops. Addition of artificial, soluble salts is regarded as by-passing nutrient release from the soil and is thus considered an unnatural form of supply. This argument sounds convincing but has no basis in science.

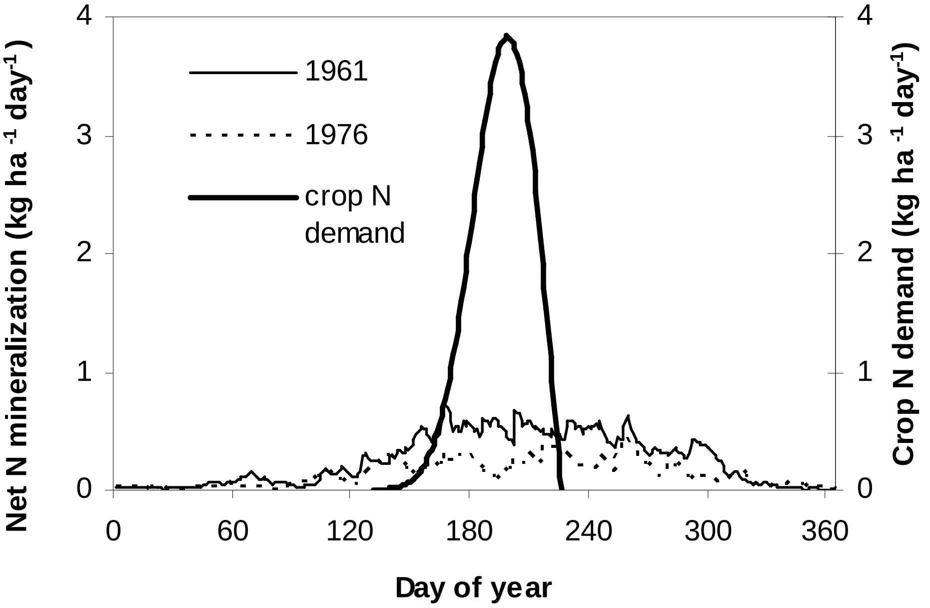

Figure 1. Amounts of nitrogen mineralised from soil organic matter during two extreme years (1961 and 1976) and typical daily N demand of a barley crop for optimum growth.
Based on data from a clay soil (0-30 cm depth) in Uppsala, Sweden.

Whereas in natural ecosystems, for example in forests, nutrient release from soil organic matter and uptake by trees can take place all year round due to the permanent vegetation and a living root system active throughout the seasons, the situation is very different in arable systems. Annual agricultural crops grow only during a couple of months, during which period they require a high rate of nutrient supply to produce a large biomass. Living roots only exist during this growth period.

Consider an example from a cold-temperate zone in central Sweden, Uppsala. To grow spring barley in this region takes less than four months. A well-grown crop takes up about 150 kg of nitrogen per hectare and about 50% of this amount must be available to the crop during a three-week period (Fig. 1). However, the most fertile topsoils in this region deliver less than 1 kg N ha^{-1} per day^{-1} during the cropping period and, on average, only 70 kg N ha^{-1} over the whole year. As can be seen in Fig. 1, annual rates of N release also vary greatly between years. Total amounts released were about twice as high in 1961 as in 1976, i.e. 92 and 47 kg N ha^{-1}, respectively, but during both these years about 50% of the mineralisation occurred outside the barley growing season. The calculations of daily rates of nitrogen release are based on a climate index (Andrén et al., 2007) using mean climatic data for the period 1956-1999 and transfer functions (Kätterer et al., 2006; Kätterer and Andrén, 2008), and assuming that most of the organic matter in soil is stabilised (Kätterer and Andrén, 2001).

In the example above, the barley crop will be able to take up 10-20 kg of N ha^{-1} accumulated before sowing plus a similar amount of N derived from mineralisation during crop growth. In total, crop uptake of 40 to 50 kg N ha^{-1} results in poor growth without any further addition of plant-available nitrogen. At least 30% of the total mineralisation per year takes place after crop harvest.

Moreover, meeting crop demand through fertilisation with organic manures is no guarantee of sufficient crop supply. Again, climate controls the decomposition of organic components and although manures stimulate biological activity in soil, the course of nutrient release is even less predictable. Organic manures may mineralise or immobilise N depending on the chemical properties of the material, particle size, spatial distribution in soil and time of application. The possibility of matching N release from organic manures with crop demand is therefore quite difficult. Again, N is mineralised when no crop is present and can easily be lost from the soil as gases or through leaching during the cold and wet autumn (see Chapter 7 of this book; Bergström et al., 2008).

It can be argued that cold-temperate climatic conditions have no representativeness and therefore limited relevance as proof of evidence. In fact, analysis of biological activity in soils in different climatic zones in Africa (Andrén et al., 2007) has shown that there is better synchrony between release and uptake of nutrients under warm climatic regimes. Crops are sown at the beginning of a rainy period and nutrients are only released during crop growth. However, synchrony between nutrient release and crop demand under certain climatic regimes does not mean that sufficient nutrients are released. Crops may still suffer from undernourishment or imbalances when only supplied with nutrients from soil biological actions.

Our conclusion is therefore that the argument by Rusch (1978) against inorganic fertilisers is not corroborated by scientific evidence, as only water-soluble nutrient sources can supply crops sufficiently and in synchrony with their demand.

2.4. Can enhancing the soil biological community improve plant nutrient availability in organic systems?

It is often assumed that the soil biological community is enhanced by organic management, developing a greater capacity to supply plants with nutrients from poorly soluble inorganic and organic sources. However, as indicated in Fig. 1, the main factors driving decomposer activity in soil are moisture and temperature. Only a larger input of organic material stimulates the biological community and leads to increased nutrient availability. Consequently, if the input of organic material is not larger in organic systems than in their conventional counterparts, or if organic yields are lower than in conventional production, the soil biological community and its activity will not be enhanced relative to conventional systems (Ryan, 1999).

Soil organic matter content has been reported to be higher in organic systems (Reganold, 1988; Wander et al., 1994; Liebig and Doran, 1999), lower in organic systems (Lützow and Ottow, 1994; Petersen et al., 1997), or unchanged (Derrick and Dumaresq, 1999; Burkitt et al. 2007) compared with conventional systems. This variety of results reflects different crop sequences and/or addition of different amounts and types of organic inputs and tillage operations (Robertson and Morgan, 1996). Higher addition of organic matter in either system is naturally followed by a larger microbial biomass (Gunapala et al., 1998; Fliessbach and Mäder, 2000). There is no evidence that a larger microbial biomass changes basic relationships in soils (Kirchmann et al., 2004), such as those between concentrations of soil available nutrients and plant nutrient uptake and growth (Ryan, 1999; Ryan and Ash, 1999; Ryan et al., 2000). However, addition of organic matter can in some instances suppress pathogenic organisms through enhancing the presence of groups of antagonistic soil organisms (Sivapalan et al., 1993; Workneh and van Bruggen, 1994).

Overall, our conclusion is that the general claim that organic practices automatically stimulate an enlarged soil biological community and that this can partly substitute for inorganic fertilisers is inaccurate.

2.5. Different roles of organic and inorganic fertilisers

We want to stress that organic and inorganic fertilisers have different functions in soil and complement each other. While input of organic manures contributes to the build-up of soil organic matter, increases the cation exchange capacity, supports soil structure, helps to chelate micronutrients, increases soil moisture retention, etc., inorganic fertilisers supply crops with nutrients at times when their demand is large. All functions are of importance but only in conventional agriculture is both management of soil fertility and crop supply with plant-available fertilisers an explicit strategy. Focusing solely on soil fertility management and prohibiting the use of artificial fertilisers means setting aside the demands of crops. As a result, crops in organic agriculture are often grown in nutrient-deficient conditions far below their production potential (see Chapter 3 of this book; Kirchmann et al., 2008). From the view of crops, use of artificial fertilisers does not mean by-passing natural processes but complementing nutrient release to fulfil crop demand.

Reliance on untreated minerals and organic fertilisers on organic farms often results in poor use efficiency of the nutrient source and lower yields than can be achieved with artificial fertilisers, particularly in regions where native soil fertility is low. For instance, field experiments with approved organic fertilisers in Europe showed that meat-bone meal and chicken manure increased grain yields only moderately (by 600 to 1500 kg ha^{-1}) compared with an unfertilised control at application rates of 40 to 120 kg N ha^{-1} (Lundström and Lindén, 2001). Crop utilisation of N was only 30% compared with 60-80% for inorganic fertilisers (Mattsson and Kjellquist, 1992). In a study of spring wheat fertilised with meat-bone meal, N-utilisation was only 13% (Wivstad et al., 1996).

3. NUTRIENT SUPPLY IN ORGANIC SYSTEMS

3.1. Are organic farms self-sustaining?

There is a widespread belief, as proposed by Steiner (1924), that self-sustaining farms are the real core of sound agricultural production. The need to import nutrients to a farm is considered a sign of failure of the system (Steiner, 1924). Traditional agricultural systems in Europe and elsewhere are often held up as the ideal in this context. The view that optimal measures to maintain nutrient levels in agricultural soils involve a high degree of on-farm recycling of nutrients, with any small losses balanced by soil weathering, is common (IFOAM, 2006). However, despite internal cycling of nutrients on farms, any agricultural production brings about unavoidable nutrient losses through leaching, runoff, gaseous emissions, etc., but the largest removal of plant nutrients from the farm is through export and sale of harvested crops and animal products. The farm is an open system and even efficient internal recycling is not sufficient to balance nutrient budgets (see Table 2).

Over the long-term, any agricultural system will become depleted in nutrients if lost or sold nutrients are not replaced. The view of a farm as a self-sustaining unit (Steiner, 1924) is in contradiction to the 'law of nutrient replacement', where nutrient removal must be restored to maintain soil fertility and avoid nutrient mining of soils. The idea of organic agriculture having a closed nutrient cycle on farms is not based on reality.

Examples of nearly self-sustaining farms or agricultural systems are rare, unless there is regular addition of nutrients from an external source. Situations where this occurs without human intervention, for example silts deposited in annual floods, appear rare (Newman, 1997) and are certainly not common enough to produce adequate food for an increasing world population. Agricultural history in Europe also tells an instructive story of how former agricultural practices in northern Europe aimed to counteract depletion of nutrient contents in cropped soils through labour-intensive removal and transport of organic matter from adjacent ecosystems to these soils. Surface layers and litter from natural ecosystems (heathlands, wet grasslands, peat, meadows) containing plant nutrients and enriched in organic material were transferred to arable soils. The mechanism behind the build-up and maintenance of Plaggen (organic matter enriched) soils was the transfer of plant nutrients through soil and litter from natural ecosystems to arable soils for several hundred years (Pape, 1970; Pott, 1990). Despite this enormous transfer, organic matter and nutrient status in arable soils remained low (Springob and Kirchmann, 2002), whereas natural ecosystems were depleted in nutrients. Thus, nutrient depletion of natural ecosystems was necessary to compensate for losses and removal from agricultural soils in order to maintain yields. In other words, already in former times, removal and losses of nutrients were compensated for by equivalent input to avoid depletion of arable soils.

3.2. Nutrient balances of organic farms

We examined P and K budgets of organically managed farms to evaluate whether the law of nutrient replacement is being followed. Nitrogen was excluded from the evaluation as nitrogen budgets are dependent on a number of factors, e.g. whether multi-year or single legume crops are grown in the rotation, etc.

This review of nutrient balances (see Table 2) revealed that purchased feedstuffs and straw played a key role as nutrient sources for mixed organic systems. Out of 19 mixed farms, 17 imported feedstuffs and 13 imported straw. On average, organically managed farms with animals had a slight surplus of +1 kg P and +5 kg K ha^{-1} yr^{-1}, whereas farms without animals had negative budgets amounting to -7 kg P and -22 kg K ha^{-1} yr^{-1}, on average, which means that the import was not sufficient to balance removal.

Organically managed farms without animals and without any nutrient import resulted in even larger deficits of P amounting to -10 kg P ha^{-1} yr^{-1}. These deficits are in the same order of magnitude as amounts removed from the farm by e.g. a well-grown organic barley crop (3.5 Mg ha^{-1}) of kg 10 P and 15 kg K ha^{-1} yr^{-1} in the form of grain. These data clearly show that the strategy of being independent of nutrient purchase according to the ideal of a self-sustaining system has no scientific support. Organic systems are not sustainable without purchase of nutrients, and use of off-farm products is necessary to counteract depletion and keep deficits of P and K to a minimum. However, despite removed nutrients being replaced through purchase, there is concern that the level of available plant nutrients in soil may decrease. Nutrients become less plant-available in organically managed soils over time addressed below.

Table 2. Farm-gate and soil balances for P and K in organically managed systems (n=37)

System, farm andcountry	Farm-gate balance[a] (kg ha^{-1} yr^{-1})		Type of purchase of nutrients	Reference
	P	K		
With animals				
Talhof, Germany	-2	1	Straw, fishmeal, feedstuff, seaweed	Kaffka and Koepf (1989)
Brynllys, U.K.	2	6	Straw, silage, hay, feedstuff,	Fowler et al. (1993)
Lea Hall, U.K.	21	53	Straw, poultry manure, feedstuff	Fowler et al. (1993)
Boschheidehof, Germany	-3	-65	Feedstuff, kieserite	Nolte and Werner (1994)
Kowai, New Zealand	-7	n.a.	None	Nguyen et al. (1995
Temuka, New Zealand	4	n.a.	P rock + elemental S	Nguyen et al. (1995
Templeton, New Zealand	-4	n.a.	Fish manure, P rock + elemental S	Nguyen et al. (1995
Kirchweger farm, Austria	2	12	Straw, feedstuff, mineral feed	Wieser et al. (1996)
Farm A, Austria	1	1	Straw, feedstuff, mineral feed	Wieser et al. (1996)
Farm B, Austria	-1.5	0	Straw, feedstuff, mineral feed	Wieser et al. (1996)
Farm C, Austria	-1	19	Straw, feedstuff, mineral feed	Wieser et al. (1996)
Farm D, Austria	3	0	Straw, feedstuff, mineral feed	Wieser et al. (1996)
Farm E, Austria	-1	1	Straw, feedstuff, mineral feed	Wieser et al. (1996)
Farm F, Austria	2	3	Straw, feedstuff, mineral feed	Wieser et al. (1996)
Farm G, Austria	-2	-1	Straw, feedstuff, mineral feed	Wieser et al. (1996)
Farm H, Austria	6	2	Straw, feedstuff, mineral feed	Wieser et al. (1996)
Öjebyn, Sweden	3	0	Feedstuff including minerals	Fagerberg et al. (1996)
Skilleby, Sweden	-3	-6	Feedstuff	Granstedt (2000)
Öjebyn, Sweden	1	59	Straw, feedstuff	Gustafson et al. (2003)
10 Farms, Australia	-17	n.a.	P rock	Burkitt et al. (2007)
Without animals	Soil balance			
Three trials, Sweden	-10	-28	None	Ivarson and Gunnarsson (2001)
Apelsvoll site, Norway	-14	-20	None	Eltun et al. (2002)
Farm no. 5, U.K.	-8	-21	None	Berry et al. (2003)
Farm no. 8, UK	-1	-52	Phosphate rock	Berry et al. (2003)
Mellby site, Sweden	-6	-2	Potash	Torstensson et al. (2006)
Lanna site, Sweden	-7	-15	None	Aronsson et al. (2007)

[a] The farm-gate balance does not necessarily take into account losses from the soil, which further decreases the figures given; soil balances sometimes include losses through leaching and runoff but not necessarily.

3.3. Conventional agriculture as a nutrient supplier of organic systems

Organic farmers can purchase a number of approved products as nutrient sources instead of artificial fertilisers (see Table 3). These products can consist of minerals, food and industrial wastes, and products derived from conventional agriculture. A primary question here is the type of nutrient source generally purchased by organic farmers. Another point of interest is whether organic agriculture mainly purchases products from conventional production and is thus dependent on this type of agriculture. To answer these questions, we evaluated the type and frequency of nutrient sources used in the studies cited in Table 2 and case studies of Swedish farms (Nyberg and Lindén, 2000), see Table 3.

The compilation in Table 3 shows that in total, 75% of all organic crop-animal farms purchase fodder products from conventional agriculture. In Australia and New Zealand, however, rock phosphate applied to pastures was purchased by about 50% of organic farms. Import of straw was more frequent (40%) to organic farms than import of manures (9%). Only on organic farms without animals did imported manures play a major role as a nutrient source (27%). The EU Directive (91/676/EC) permits purchase and application of manures and composts to organically managed systems from conventional farms equivalent to 170 kg N ha^{-1} yr^{-1} unless there are changes in the regulations. Such an amount means that crops in organic agriculture can be completely supplied with manures from conventional production. Seeds seem to originate from conventional production throughout, although information is incomplete. Our data corroborate what Watson et al. (2002b) referred to as a '*cause for concern in relation to the sustainability of dairy farm systems because of their dependence on imported feedstuffs and bedding for P and K, and for N on the very variable fixation of legumes or imports of manures or compost*'.

Data in Table 3 refer to conditions when it was permissible for organic farmers to purchase feedstuffs from conventional production. These conditions have changed within the EU countries since then. A recent regulation aims to prohibit the use of conventionally grown fodder within organic animal production from 2005 onwards (European Communities, 1999). Little information is available about the current situation but regarding Sweden there is little organically produced fodder available on the market. Indeed, exemptions have been granted to continue use of conventional fodder for organic animal production.

Our conclusion here is that despite official regulations, organic agriculture is reliant on nutrients derived from conventional farming and is not sustainable with respect to nutrient supply. This dependence, and thus non-sustainability, is seldom recognised or pointed out. Moreover, the reliance of organic systems on production systems fertilised with inorganic fertilisers cannot be maintained if a large proportion of conventional farms convert to organic agriculture. If organic farming were to become the dominant form of agriculture, there would be no surplus of fodder, straw or manure. The transfer of nutrients from conventional to organic production would stop and only untreated minerals would remain purchasable for organic farms.

In Sweden, it is also permissible to apply meat meal, bone meal, and wastes derived from food industries (Swedish Control Organisation for Alternative Crop Production, KRAV, 2008), which is a further reliance on nutrients from conventional production. An assessment of the nutrient import through these sources to organic production (information provided by the main Swedish retailer Svenska Lantmännen in Enköping) indicates that noteworthy quantities of nutrients are transferred to organic fields amounting to about 3 kg N, 1.4 kg P and 5 kg K ha^{-1} yr^{-1}.

Table 3. Use frequency of approved materials in organic agriculture.

	Use frequency (number of farms)	
Approved materials	Crop-animal farms (n=35)	Crop farms (n=11)
Agricultural products		
Concentrate and feedstuffs[a]	17 (49%)	
Manure	3 (9%)	3 (27%)
Mineral fodder	9 (26%)	
Nutrient-fortified soils[b]		
Seed	35 (100%)	11 (100%)
Straw	14 (40%)	
Wastes		
Ash of wood, straw, peat, cereals		
Digested residues		
Fish meal	2 (6%)	
Meat and bone-meal		1 (9%)
Basic slag	1 (3%)	
Vinasse		
Minerals		
Calcium carbonate		
Dolomite		
Elemental sulphur	2 (6%)	
Gypsum		
Halite		
Kainit		
Kieserite	1 (3%)	
Phosphate rock	17 (49%)	1 (9%)
Potassium magnesia		
Rock powder		

[a] Purchase of fodder by organic farmers from conventional agriculture has been banned by an EU-regulation since 2005 (European Communities, 1999).

[b] The residual effect of inorganic fertiliser application on soil fertility before organic cropping principles has not been considered.

A further form of nutrient supply from conventional to organic agriculture is through residual nutrient reserves in soil built up prior to conversion to organic cropping principles. The fertility of most conventionally managed soils has been increased through long-term applications of inorganic P and K fertiliser. Previous use of inorganic fertiliser for one or several decades improved the nutrient status of conventionally managed soils. However, the history of nutrient application prior to organic crop production is rarely mentioned and most often not considered in the results. In fact, few organic farms have never received any inorganic fertilisers.

Applying organic cropping principles on previously nutrient-fortified soils has at least two consequences. The plant availability of nutrients in soil again declines to low levels similar to those before application of artificial inorganic fertilisers, since organic agriculture can only apply less soluble nutrient sources. Thus, the pool of plant-available nutrients is mined and not replaced. Furthermore, yields may fail to increase and may even decline over time (see Chapter 3 of this book; Kirchmann et al., 2008b).

3.4. Changes in P and K status of organically managed soils

Although the law of nutrient replacement may be followed in organic agriculture, addition of nutrients is only one of two essential conditions to maintain soil fertility. The second most important condition is that the nutrients added are more plant-available than the existing nutrients in soil. If not, fertility will decline despite nutrient replacement and maintenance of nutrient stocks in soil. Our review of studies on this subject indicates that lower plant availability of nutrients in organically managed soils over time is common.

Reduced concentrations of plant-available P and K were measured in nutrient-rich soils in Norway within five years of conversion to organic practices by Løes and Øgaard (1997). The same authors reported that extractable P on five Norwegian dairy farms decreased over time (Løes and Øgaard, 2001). Similarly, in Denmark Askegaard and Eriksen (2000) reported that K was limiting for growth of barley and clover ley crops on sandy soils after only a few years of organic farming. Gosling and Shepherd (2005) investigated extractable K and P in English soils managed organically and found significantly lower contents on the oldest organic farm compared with conventional fields. Torstensson et al. (2006) found that at a Swedish site, organic management meant a reduction in plant-available nutrients after only a few years. In the organic rotation at that site, potassium carbonate had to be applied in order to avoid complete crop failure of potatoes.

Evans et al. (2006) found very low concentrations of plant-available P on organic farms in New Zealand. Similar results were reported from organic farms in Australia by Burkitt et al. (2007). Rock phosphate, commonly used to maintain a positive P balance on organic farms in Australia and New Zealand, resulted in a low plant availability of P relative to neighbouring conventional farms (Nguyen et al., 1995; Derrick and Dumaresq, 1999; Ryan et al., 2000). In southern Australia, low P inputs to biodynamic farms (2 kg ha^{-1} yr^{-1}) contributed to a negative P balance (-17 kg ha^{-1} yr^{-1}) compared with a small positive balance on conventional farms (2.3 kg ha^{-1} yr^{-1}), which received 19 kg P ha^{-1} yr^{-1} (Burkitt et al., 2007). For instance, Derrick and Ryan (1998) found that compared with a conventional neighbouring farm, cereal grain from an organic farm was P-deficient and had poor seedling vigour. Thus, P deficiency can even indirectly feed back through the systems and limit yield (Ryan et al., 2004).

Overall, there are no indications that plant availability of P and K in soil can be maintained through organic management. Moreover, there is a risk that a lower plant availability over time may also be true for nutrients other than P and K.

4. IS THE ‘NATURALNESS’ OF PLANT NUTRIENT SOURCES A RELEVANT QUALITY CRITERION?

The literature on organic agriculture describes ‘naturalness’ to be a prerequisite for sound food production (see Chapter 2 of this book; Kirchmann et al., 2008a). We argue, however, that ‘naturalness’ of compounds cannot be used as quality criterion. We discuss limitations and disadvantages related to the use of two natural nutrient sources, legumes and phosphate rock, as compared to the use of artificial fertilisers.

4.1. Use of legumes as a natural nitrogen source

One plant macronutrient that enters agricultural systems without direct import is nitrogen through legume cropping. In fact, legumes can provide larger amounts of N than recommended N fertiliser rates. Using legumes in a crop rotation to obtain free N seems at the first glance straight-forward. However, only in systems with legumes grown year after year, such as permanent pastures or grassland, is there a continuous input. In all other cropping systems, legumes must provide N even for the following non-leguminous crop. On organic farms without animals, years with green manure legumes are part of the rotation to substitute for the exclusion of N fertilisers, which requires land to be set aside for green manure crops.

Thus, the actual cost of replacing N fertiliser with green manure years is a reduction in crop production due to years with non-harvested crops. A comparison of N supply in an organic and conventional cropping system without animals (Fig. 2) illustrates the difficulties associated with the exclusive use of legumes as a major N source.

According to data from Torstensson et al. (2006), the N input in an organic rotation can amount to 40-50 kg N ha^{-1} yr^{-1} for a legume sown together with a main crop. Only full green manure years provide large amounts (140-160 kg N ha^{-1} yr^{-1}) which are higher than those applied with inorganic N fertiliser. Over a rotation, Torstensson et al. (2006) found mean amounts of N fixed through legumes to be about 70 kg N ha^{-1} yr^{-1} in the organically managed system, whereas 97 kg N ha^{-1} yr^{-1} was applied in the conventional.

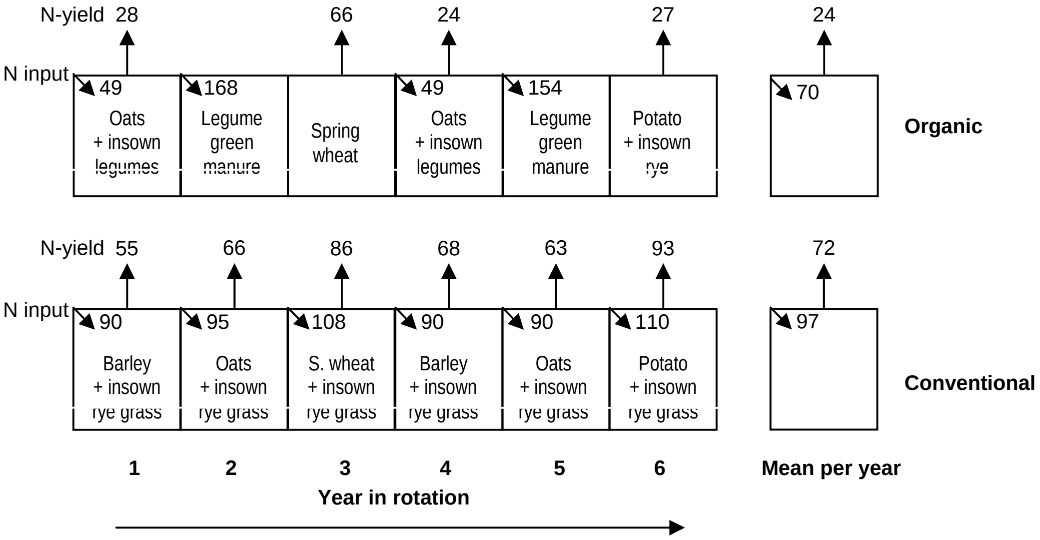

Figure. 2. An example of input and yield of nitrogen using legumes in an organic crop rotation and fertiliser application in a comparable conventional rotation. Data from Torstensson et al. (2006) and Torstensson (pers. comm. 2008).

In the conventional system, N input matched the demands of the crop. In the organic system, N input was not adapted to the need of the following crop being either too high or too low. Furthermore, N release from green manure legumes is not necessarily synchronised with the demands of the following crop. As shown in Chapter 3 of this book (Kirchmann et al., 2008b), crop utilisation of N from organic manures is lower than from artificial N fertilisers. The possibility of a following crop utilising legume N is relatively low, often less than 30% (e.g. Marstorp and Kirchmann, 1991; Wivstad et al., 1996; Dahlin et al., 2005) due to decomposition of material legume at times when there is no crop demand. Even over the long term, the agronomic efficiency of legume N is much lower than of artificial N fertiliser (Kirchmann et al., 2007). Consequently, leaching of legume N is often higher than from artificial fertiliser (see Chapter 7 of this book; Bergström et al., 2008).

4.2. Low plant availability of P from phosphate rock

Of all major plant nutrients, P is the one for which global reserves are most limited and which must be used efficiently. The estimated life-time of economically viable P reserves varies between 50-100 years (Driver et al., 1999; Isherwood, 2003), while for known total world reserves it is around 340 years (Stewart et al., 2005).

In organic agriculture, untreated minerals such as phosphate rock are used instead of water-soluble P fertiliser. However, one of the major drawbacks related to the direct use of phosphate rock is its poor solubility. Most sedimentary and igneous phosphate rocks have a low reactivity in near-neutral and calcareous soils and only a small group of so-called ‘reactive’ phosphate rock types have a similar solubility to artificial phosphate fertilisers (Buresh et al., 1997). The high reactivity of these specific phosphate rock types is explained by differences in their molecular structure, whereby a large proportion of the phosphate ions is substituted by carbonates. The majority of phosphate rock types, however, are highly insoluble and supply small quantities of P to crops, as was discovered a long time ago (e.g. Robertson, 1922). As mentioned above, under certain soil conditions - low soil pH, low exchangeable Ca and low P concentrations in the soil solution - phosphate rock may release more P than the natural phosphate in soil (e.g. Robinson and Syers, 1990; Rajan et al., 1991) and its use can be effective (e.g. Mengel, 1997). However, acid conditions in agricultural soils are undesirable for several reasons and are normally corrected by liming. Thus, the application of phosphate rock to soil is only useful if the material has a significantly higher solubility than the natural phosphate in soil (Hedley and McLaughlin, 2005).

In an attempt to increase the solubility of phosphate rock, materials have been added to composts in order to increase the plant availability of P through biological reactions taking place during composting. During the initial, mesophilic phase of composting lasting a couple of days, organic acids are formed, resulting in a slight decline in the pH of the compost, which favours the dissolution of phosphate rock. Accordingly, phosphate rock should become more plant-available during this stage of composting, which in fact has been corroborated by Singh and Amberger (1998). However, during further composting accompanied by an additional rise in temperature, the organic acids are rapidly broken down and a drastic rise in compost pH is recorded (Epstein, 1997; Beck-Fries et al., 2003). In mature composts, pH values range from 7 to 9, which is too high to dissolve phosphate rocks (e.g. Mahimairaja et al., 1995). Even nitrification in mature composts, producing protons, has no major effect on the dissolution of P as the pH remains above neutral (Mahimairaja et al., 1993). Consequently, field trials with compost amended with phosphate rock compared with compost without phosphate rock revealed no significant difference in yield (e.g. Nyirongo et al., 1999). These findings are in agreement with our understanding that chemical reactions in compost rather than biological reactions determine the P solubility of phosphate rock and that composting does not provide favourable conditions for P dissolution due to high pH values.

An area where organic farmers rely heavily on rock phosphate to supply P to organic crops is southern Australia, where growing season rainfall may be as low as 250 mm and soil extractable bicarbonate P less than 20 mg kg^{-1}. Crop nitrogen requirements are met through N_2-fixation in a preceding legume-based pasture ley. However, in this environment, rock phosphate provides no immediate benefits to crop P-nutrition or growth (Dann et al., 1996; Ryan et al., 2004). The resulting P-deficient status, often coupled with high weed levels, is the primary cause of substantially lower yields in organic systems compared with conventional (Kitchen et al., 2003; Ryan et al., 2004). In many cases, larger amounts of phosphate rock P than water-soluble P fertilisers are applied (e.g. Rajan et al., 1991; Johnston, 2005; Evans et al., 2006) to compensate for low water solubility. Use of reactive phosphate rock slightly improves yields under highly acid soil conditions (Evans et al., 2006). The results also indicate that maintaining the supply of plant-available P with phosphate rock would require more resources. For instance, the long-term use efficiency of phosphate rock applied at 4 Mg ha^{-1} (646 kg P) amounted to only 7% P, compared with 36% from soluble P fertilisers (519 kg P) over 18 years (Kirchmann et al., 2007). The low residual effectiveness of phosphate rock has been discussed by Rajan et al. (1996).

The inefficiency and thus the demand for larger amounts of phosphate rock P can also be criticised from the perspective of conserving a non-renewable and limited global resource. Using only untreated phosphate rock can lead to a faster exploitation rate than with processed P fertilisers, shortening the life-time of phosphate reserves.

4.3. Contaminating soil-plant systems with cadmium through P sources

A further disadvantage of using phosphate rock is the potential contamination of soils with cadmium (Cd), as Cd cannot be removed from phosphate rock without chemical treatment. Most phosphate rock contains Cd as impurities substituting Ca in the lattice of hydroxyl apatite. As the oxidation state of both Cd and Ca is 2+ and the Pauling radius of Cd (97 pm) is similar to that of Ca (109 pm), these similarities along with a preference for six-fold coordination facilitate the substitution of Cd into specific Ca sites in phosphate minerals. Cadmium impurities in phosphate rock and phosphorus fertilisers can lead to accumulation in the food chain, since Cd is highly mobile in the soil-plant-system, and there is a risk that excessive Cd absorption can affect human health (McLaughlin and Singh, 1999).

A review of the Cd content of phosphate rock of different origins shows that concentrations vary from 1 up to 600 mg Cd kg^{-1} P, with most reserves having concentrations higher than 50 mg Cd kg^{-1} P (McLaughlin et al., 1996). The largest reserves in the world are minerals of sedimentary origin located in Africa and the USA and have moderate to high Cd concentrations, with only minor reserves (e.g. in Northern Russia and Finland) having low Cd contents.

Applying untreated phosphate rock at a rate of e.g. 250 kg P assuming a mean concentration of 100 mg Cd kg^{-1} P would mean an addition of 25 g Cd ha^{-1}. Relating this figure to the mean Cd content of Swedish arable land, which is 0.23 mg Cd kg^{-1} soil (Eriksson et al., 1997), the Cd content of the upper 10 cm soil layer would be increased by 10%. Andersson and Siman (1991) showed that Cd concentrations in crops and seeds consistently increased with increasing P application when the

P source contained 70-150 mg Cd kg^{-1} P. At the same time, medical research indicates that the safety margins in food may be smaller than believed so far (Buchet et al., 1990).

The technical know-how to extract Cd and other impurities efficiently and at a low cost from phosphate rock has been developed recently (Cohen, 2007a,b). Thus, in contrast to phosphate rock, artificial P fertilisers low in Cd can be produced even from highly cadmium-rich P sources in the future.

The discussion makes clear that there are major shortcomings using natural nutrient sources. ‘Naturalness’ is not a guide-lining authority guaranteeing higher quality.

5. IS NUTRIENT RECYCLING ENHANCED BY ORGANIC FARMING?

Two nutrient flows can be distinguished as regards recycling. One flow is of nutrients within or between farms, the so-called farm cycle, while the other is of nutrients exported from farm to society and recycled back to the farm, the so-called food cycle.

In Europe, there is a long tradition of recycling nutrients on farms and of re-applying them to arable land. Careful collection of animal wastes, conservation during storage and careful application to soil to minimise losses were well-founded practices long before artificial fertilisers became available. However, practices concerning recycling of wastes other than agricultural waste have been less successful in Europe (Kirchmann et al., 2005). Advanced recycling practices for wastes from society have only been developed in the Far East. For example, King (1911) described nutrient recycling through extensive transport of urine, pulverised human excreta, ash, compost and mud by human- or animal-drawn carts and boats from large cities in China, Korea and Japan back to agricultural land. It is obvious from King’s description that careful collection and storage are labour-intensive practices but also that equitable redistribution of nutrients from society back to agricultural land enabled more sustainable production than in Europe or the USA.

There is no doubt that the sustainability of most agricultural systems could be improved through an increased emphasis on recycling and greater return of nutrients in municipal wastes and off-farm products. The central question here is whether organic practices improve the recycling of nutrients in general.

Once again, the other condition required for sustainability of agricultural systems must be borne in mind, namely that the plant availability of recycled nutrients must be higher than that of nutrients in soil in order to maintain production levels. Thus, although a high degree of nutrient recycling is positive and minimises losses from agricultural systems, this is no guarantee of efficient utilisation by crops and maintenance of yields.

5.1. Recycling on-farm nutrients

Organic farmers recognise on-farm animal manures as a valuable source of nutrients and place much emphasis on proper use of manures in a crop rotation. The common opinion is that organic farmers are therefore better at taking care of on-farm wastes as they are forced to do so due to shortage of nutrients. However, this belief is in contrast to how manure must be treated according to the rules in biodynamic and biological organic agriculture.

Biodynamic farmers must compost solid animal manures (Steiner,1924), resulting in high losses of N in the form of ammonia (Kirchmann, 1985). This practice, which is central for biodynamic agriculture, leads to the least efficient recycling of N and organic matter compared with other forms of manure treatment. The concept of only surface-applying manure or green manure crops as proposed by Rusch (1978) in biological organic farming also favours losses of ammonia N.

In fact, efficient methods to decrease ammonia volatilisation from animal wastes have been developed within conventional agriculture (Bussink and Oenema, 1998; Gustavsson, 1998). These methods involve anaerobic storage of solid manures, covering slurry and urine tanks, incorporation of animal wastes into soil within four hours of spreading, direct soil injection, and regulation of manure storage capacity and spreading periods. Furthermore, best management practices for manures are easier to apply in conventional agriculture where science-proven rather than nature-based ideas guide decision-making. Good intentions in organic agriculture are insufficient if fundamental practices cannot be changed due to a dogmatic foundation. Still, several on-farm measures to minimise nutrient losses from manures and to utilise nutrients in an optimal way in relation to crop needs are independent of whether the production is organic or conventional.

Advocates of organic agriculture often point out that mixed crop and animal farming and a balance between animal and crop production is a principle guaranteeing efficient on-farm recycling of nutrients (e.g. Granstedt, 2000). This principle is similar to the idea that farms should be self-sustaining, not requiring an input of fodder or nutrients. Mixed farming is a straight-forward solution to avoid nutrient imbalances caused by a large import of feedstuffs, which contributes to an excessive supply at the local or regional level. However, specialisation of single farms does not necessarily mean a surplus of nutrients and inefficient recycling. An excess of manure can be re-distributed within an acceptable area to adjacent farms. Another measure is to prevent a further increase in animal density by limiting the number of farm animals in relation to arable land available regionally (Sims et al., 2005). However, specialisation such that farms in a whole region carry out the same production can have a negative environmental impact. On the other hand, re-introducing mixed farming on a large scale may be difficult and may put the farm’s economy at risk.

5.2. Recycling off-farm nutrients

Production and sale of agricultural products and thereby outflow of nutrients from farms is an essential part of the food supply. In contrast to on-farm recycling, nutrients exported to the food cycle are far more difficult to return to arable land. The bottlenecks for recycling of nutrients in food and municipal wastes include the high cost of re-transportation of wastes from towns and cities back to rural areas and often a low value and attractiveness due to the presence of organic pollutants and unwanted or high metal concentrations.

Current regulations for organic agriculture restrict recycling of toilet wastes. As toilet wastes contain the largest proportion of nutrients exported from farms to the food cycle, significant amounts of nutrients simply cannot be returned to agricultural soils under organic production (Fig. 3). Under Swedish conditions, Kirchmann et al. (2005) determined that about 17 kg N and 2 kg P per hectare and year are present in toilet wastes that cannot be recycled to organically managed fields.

Recycling of nutrients from the food cycle back to agriculture could be greatly increased through widespread adoption of new recovery technologies enabling the extraction of nutrients from wastewater, biogas residues and other municipal wastes in pure form without organic matter and unwanted metals. For example, P can be extracted through precipitation as pure calcium phosphate (van Dijk and Braakensiek, 1984; Eggers et al., 1991; Seckler et al., 1996a,b,c; Angel, 1999) or pure magnesium ammonium phosphate (struvite) (Battistoni et al., 1997; Liberti et al., 2001; Ueno and

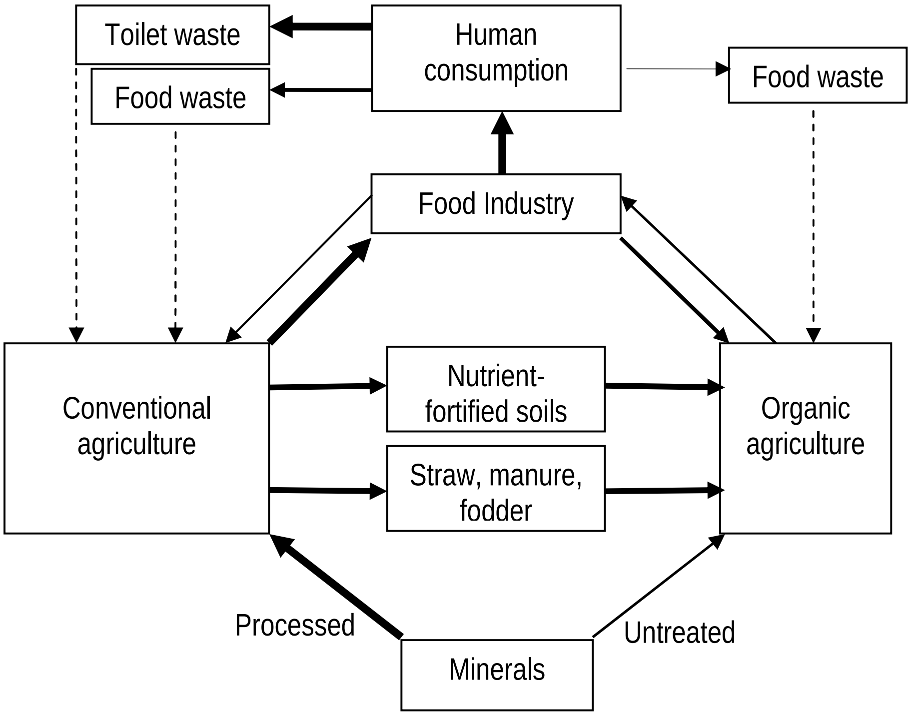

Figure 3. Nutrient flows when organic agriculture is integrated into society.

Fujii, 2001). Methods for extraction and recovery of P as ammonium phosphate from urban wastes and ashes have also been developed (Cohen, 2007a,b). Overall, recovery of nutrients in the form of concentrated, inorganic products and redistribution without organic matter may help to overcome the main bottlenecks for recycling of nutrients from municipal wastes. This may be of particular importance in countries such as Australia, where agricultural production is located long distances from population centres and processing industries. However, as the new nutrient recovery technologies will enable production of water-soluble, inorganic products, only conventional farmers may be able to use these products and thereby improve nutrient cycling.

6. CONCLUSIONS

The organic agriculture practice of excluding artificial fertilisers and being self-sustaining through cycling of nutrients was examined. Based on this literature review, the following conclusions can be drawn:

- The organic principle of excluding water-soluble fertilisers and fertilising the soil rather than directly feeding the crop with nutrients has no basis in science. Untreated minerals often have a low efficiency due to their insolubility. This limitation is not overcome through a change in the soil biological community in organically managed soils. It is also important to note that input of fully water-soluble nutrients to soil also takes place on organic farms through organic materials.

- While the soil biological community on organic farms may differ from that on conventional farms, it cannot compensate for the lack of readily available nutrients in fertilisers. The release of organically bound nutrients through soil biological activity is not necessarily synchronised with crop demands. Changes in the soil biological community do not overcome this limitation.

- Two major conditions determine the sustainability of an agricultural system. Firstly, plant nutrients removed or lost from soil must be replaced to avoid depletion. Secondly, the availability of nutrients to plants must be maintained. Both these conditions are far more difficult to fulfil through organic agriculture than through conventional fertilisation practices.

- Organic agriculture imports feedstuffs, straw, manures and food wastes, mainly originating from conventional production. Today, organic agriculture is largely dependent on nutrient transfer from conventional agriculture and is thereby subsidised by the nutrients in artificial fertilisers. In terms of closing nutrient cycles, organic farming is limited by restrictions on using municipal wastes either directly or as water-soluble, inorganic extracts.

- Overall, there is no scientific support for the idea of ‘naturalness’ as a guiding quality principle. The ‘naturalness’ of compounds is not a guarantee of their superiority. We advocate a flexible approach where farming systems are designed to meet specific environmental, economic and social goals, unencumbered by philosophical views on nature. We invite the organic movement to reconsider their opinion towards the use of modern fertilisers.

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