Energies **2011**, *4*, 804-817; doi:10.3390/en4050804

OPEN ACCESS

energies

ISSN 1996-1073

www.mdpi.com/journal/energies

Review

Utilization of Natural Farm Resources for Promoting High Energy Efficiency in Low-Input Organic Farming

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Received: 15 February 2011; in revised form: 10 March 2011 / Accepted: 9 May 2011 / Published: 12 May 2011

Abstract: Both organic and conventional farming processes require energy input in the form of diesel fuel for farming equipment, animal feed, and fertilizer compounds. The most significant difference between the two methods is the use in conventional farming of mineral fertilizers and pesticides that are minimally employed in organic management. It is argued that organic farming is more environmentally friendly, given that synthetic fertilizers mainly used at conventional farms are replaced with animal manure and cover crops. Nutrient uptake by plants is additionally enhanced by the effective use of rhizobia and other types of plant growth-promoting bacteria, in combination with arbuscular mycorrhizal fungi. This article aims to compare the amounts and/or types of energy and nutrients required for both farming systems and provide feasible suggestions for the sustainable use of farm resources in combination with good crop yields.

Keywords: energy; nutrient; recycling; organic farming

1. Introduction

Energy is essential for the survival of plants, animals, and microorganisms. Phototrophic plants, algae and specific bacterial groups can directly collect energy from sunlight to catalyze the conversion of carbon dioxide into organic molecules. However, animals and other heterotrophs require reduced carbon compounds for their reproduction and growth, and are hence dependent on phototrophs for satisfying their energy requirements. Generally, the use of cover crops in farming improves the capturing of solar energy by plants by 1.8 times [1], in addition to the beneficial nutrient and water conserving properties [2]. Moreover, leguminous cover crops contribute substantial amounts of nitrogen to the soil upon tilling [1]. Fossil and solar energy are needed for all types of agricultural farming, including organic and conventional systems. The major differences in energy requirements between these farming systems are attributable to the use of mineral fertilizers and pesticides, which are not allowed on certified organic farms [1].

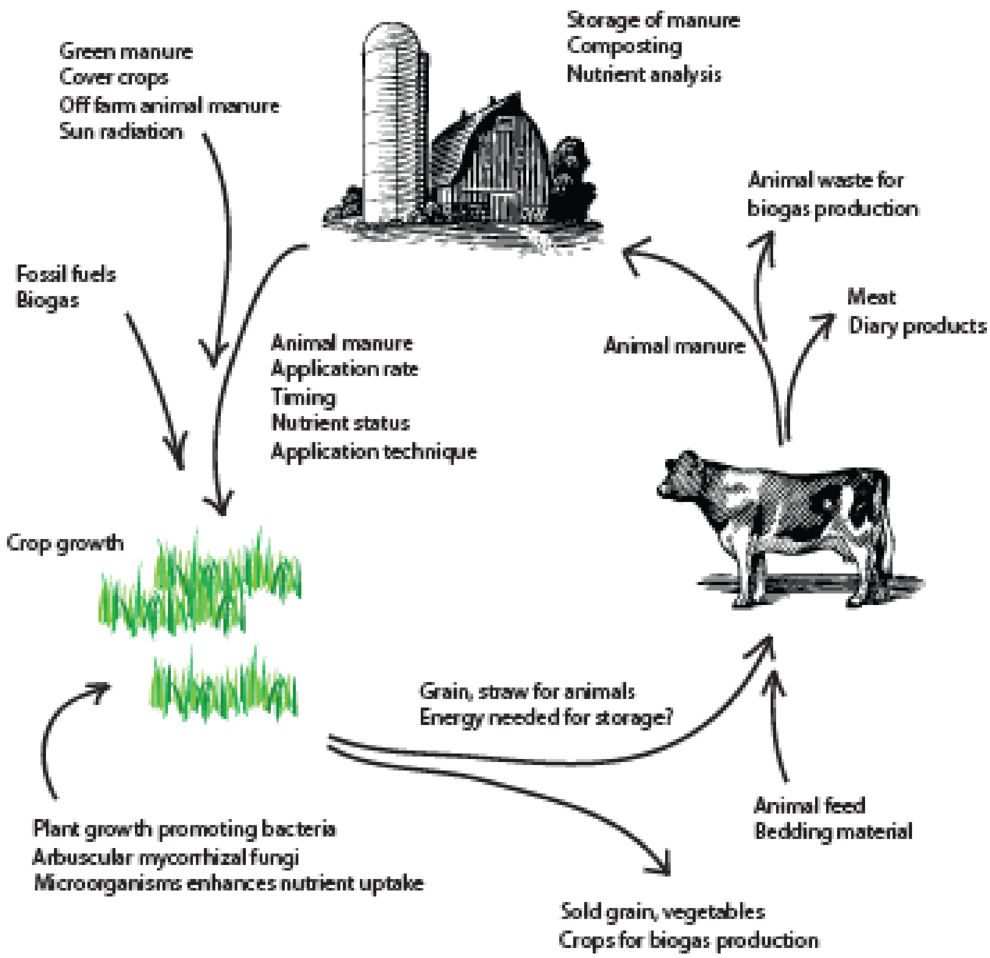
Agricultural production needs to keep up with the constantly growing human population trend in order to ensure sufficient food and meet the renewable energy requirements [3]. To date, high crop yields have been achieved by the inappropriate use of large amounts of chemical fertilizers and pesticides, previously shown to cause nutrient (e.g., nitrogen (N) and phosphorus (P)) leaching and runoff [4,5]. Nitrogen levels exceeding 50% of the amounts applied are lost as N2, leached nitrate or trace gases [4,6], whereas as much as 90% of applied P may precipitate, contributing to P pollution [7,8]. One way to protect the environment through reducing this nutrient leakage from farming systems is by ensuring the presence of crops in the field when the nutrient is made bioavailable, for example, via application of cover crops. The negative environmental impact of fertilizers has consistently been ascribed to the low efficiency of nutrient uptake [9]. One possible way to facilitate environmentally-friendly crop production with high yield would be via integrated management with no redundant fertilizer application, instead combining nutrient input with microbes stimulating plant nutrient uptake.

The main aim of this report is to compare conventional and organic farming systems, with emphasis on the energy required and nutrient sources present in each system. We have additionally evaluated the potential methods and resources that can be applied and developed further to obtain an optimal sustainable farming system with high energy efficiency.

2. Concepts in Organic Farming

Recent years have seen a steady growth in the organic farming sector in Europe, with a 21% increase in the organic farming area in the European Union between 2005 and 2008 [10]. Both farmers and consumers are concerned with the development of sustainable agriculture, improved animal welfare and healthiness of consumed food. Moreover, there has been increasing interest in locally produced food from an environmental perspective [11]. Organic farming is a holistic approach to agriculture, which takes into account environmental protection, animal welfare and consumer confidence, meaning that consumers should be able to trust organic products as healthy and fair. Societal and economical developments are important aspects of organic agriculture. The basic idea of organic farming is that each farm should be self-supporting, recycling its energy and the nutrients produced (Figure 1), thus providing an effective and environmentally friendly form of agriculture. Four principles have been formulated by the International Federation of Organic Agriculture Movements (IFOAM), termed the principles of health, ecology, fairness and care [12]. The first principle, dealing with health, may be summarized as a wish to maintain the function and wellbeing of all ecosystems and organisms living therein. The principle of ecology states that all production should be based on ecological processes and recycling, and carried out in balance with natural ecosystems in a way that protects and benefits land, water, air and biodiversity. Fairness and care should be a part of the process with respect to all parties involved in the production steps, thus ensuring an environment that can sustain our successors.

Figure 1. Energy and nutrient re-cycling in organic farming. Animal feed and bedding material are needed in order to keep animals. The farmyard manure can then be stored, preferably composted to reduce the number of pathogenic bacteria, or used for biogas production. Nutrient analysis is an important step if the manure is to be used as a fertilizer. Other types of fertilizers that can be used are cover crops and green manure. If the farm does not keep animals, or cannot produce enough manure, off-farm manure is sometimes bought from near-by farms. The application technique as well as the timing and rate of application, are very important steps to consider to minimize nutrient leaching. Fuels used for the farming equipment is often of fossil origin, but could in the future consist of biogas, in order to minimize farm dependence on fossil fuels. Plant growth promoting bacteria and arbuscular mycorrhizal fungi can be used in crop production to enhance plant nutrient uptake and to minimize nutrient leaching. The crops produced may then be stored and sold to consumers or used as feed for the farmyard animals, thus closing the farm energy cycle.



A major proportion of the energy required for both organic and conventional farming systems is fossil-based (Table 1). This energy is required for machinery fuel as well as indirectly for production of fertilizer, pesticides and farming equipment [13]. A way of minimizing the use of fossil fuels in the future would be on-farm biogas production [14], although this is not economically viable at present [15]. One theory is to produce rapeseed and grass-clover crops in order to maintain soil fertility and generate biomass for energy production in nearby biogas plants [16].

Table 1. Energy input (total energy costs), reported as GJ ha^{-1} $year^{-1}$, required for different crop species and farming systems (e.g., organic, integrated and conventional farming, respectively).

	Organic	Integrated	Conventional	Reference
Sugar beet	-	26.3	33.8	[17]
Durum wheat	-	16.9	27.1	[17]
Sorghum	-	16.0	22.9	[17]
Sunflower	-	14.8	23.0	[17]
Barley	9.0	-	13.8	[18]
Grain crops	4.8	5.2	7.1	[19]
Spring barley	12.6	-	16.6	[20]
Pea	7.4	-	10.4	[20]
Winter wheat	9.2	-	20.3	[20]
Various crops	8.1	12.4	-	[21]
Wheat-potato-clover	13.3	-	24.1	[22]
Raisin	22.2	-	28.9	[23]
Soybean	7.7	13.6	-	[24]
Maize	25.9	46.9	-	[24]
wheat	11.4	28.0	-	[24]
Soybean	9.6	-	8.8	[1]
Grain crops	24.2	-	68.4	[25]

The self-supporting theory that every farm should be a "closed system" with regard to energy and nutrients [26] and the concept of avoiding mineral fertilizers have been subjected to considerable criticism. Kirchmann *et al*. [26] argue that organic farms are dependent on nutrient and energy input from conventional farms, for example, in terms of acquiring straw or animal feed, thus relying on mineral fertilizers as a secondary step. The authors have found no scientific evidence that increased microbial activity in organically managed soil can compensate for the loss of easily bioavailable nutrients supplied by mineral fertilizers [26].

However, soil in organic systems generally contains higher organic matter than that in conventional systems. For example, conventionally managed soil consists of 3–4% organic matter whereas the corresponding value for organically managed soil is 5.2–5.5% [1,2]. Pimentel and co-workers [27] emphasized that the higher organic matter content in organically managed soil is directly related to its energy efficiency, as organic matter increases water infiltration leading to reduced soil erosion, improves soil food webs, and contributes to nitrogen cycling from within the soil [27]. Moreover, Pimentel *et al*. [1] compared corn and soybean crops produced in conventional and organic farms. The conventional farms used mineral fertilizers and pesticides according to U.S. standard dose recommendations, whereas the organic farms received no additives. The authors reported that organically produced corn and soybean consumed 30% less fossil energy on average, in combination with higher degrees of water conservation in the soil, better maintenance of soil quality and conservation of more biological resources, compared to conventional farming [1].

For effective crop and vegetable production, there is a constant need for nutrient and energy input into the soil. Mineral fertilizers have negative effects on biogeochemical cycles and enhance leakage of nutrients, mostly N and P [28]. It is suggested that the natural fertility and health of soil can be restored without the need for synthetic chemicals by using fertilizers produced on the farm, such as stable manure, green manure or composted organic material [4]. These organic fertilizers are possibly partly converted by the soil bacterial and fungal communities to more bioavailable compounds that can be taken up by plants [29,30]. Crop yield in organic farming may be only 20% lower than that in conventional farming, with a 34–51% decrease in nutrient input (N, P, potassium (K)) over a 21-year period [22]. Moreover, organically and conventionally produced corn, soybean and wheat have shown no significant differences in yield after a 4-year transition period to organic farming [1]. Certain microbial inoculants consisting of arbuscular mycorrhizal fungi (AMF), plant growth-promoting rhizobacteria (PGPR) and nitrogen-fixing bacteria enhance nutrient uptake among plants [30]. Nutrient balance in organic farms is around zero (N, P, K), with a negative balance for P and K, and review of energy consumption shows that organic farms consume less energy than conventional farms [31], along with higher energy efficiency of annual and permanent crop production (Table 2).

Table 2. Energy efficiency values, calculated as the ratio between the crop production energy output and the energy input, for different species in various cropping systems (e.g., OF, organic farming; IF, integrated farming; CF, conventional farming).

Crop	Country	Duration (years)	Energy Efficiency, OF	Energy Efficiency, IF	Energy Efficiency, CF	Reference
Apricot	Turkey	3	2.2	-	1.5	[23]
Sugar beet	Italy	12	-	2.9	2.6	[17]
Durum wheat I	Italy	12	-	7.5	5.1	[17]
Durum wheat II	Italy	12	-	6.9	4.7	[17]
Sorghum	Italy	12	-	14.1	10.1	[17]
Sun flower	Italy	12	-	17.6	11.4	[17]
Winter rye	Germany	5	34.8	23.7	20.9	[21]
Winter rye	Germany	5	44.1	22.7	-	[21]
Corn	US	22	7.7	-	5.1	[1]
Soybean	US	22	3.8	-	4.6	[1]
Spring barley	Slovakia	11	10.9	-	10.0	[20]
Pea	Slovakia	11	12.8	-	9.4	[20]
Winter wheat	Slovakia	11	16.4	-	8.2	[20]
Rice	Philippines	>3	12.7	7.0	4.7	[32]
Grain crops	US	17	11	13	10	[19]

3. Microorganisms Stimulating Plant Nutrient Uptake

An interesting alternative is to use mixed microbial inoculants consisting of arbuscular mycorrhizal fungi (AMF) and plant growth-promoting rhizobacteria (PGPR) [3] to improve crop productivity. Both AMF and PGPR contribute to enhanced nutrient uptake by plants [33], and the combined effects may be more pronounced. For example, PGPR may support AM symbiosis by increasing the amount of bioavailable phosphate. In soil with low P availability, free-living phosphate-solubilizing bacteria release phosphate ions from sparingly soluble inorganic and organic P compounds [34], contributing to the soil phosphate pool available for extraradical AM fungal hyphae to forward to the roots [35]. Linderman showed a strong stimulatory effect of PGPR on AM fungal growth [36], whereas Azcón reported induction of growth of mycelia from *Glomus mosseae* spores by an identified PGPR [37]. Co-inoculation of selected PGPR and AMF may thus be applied to optimize the formation and function of AM symbiosis. Despite considerable research focus on the interactions between specific strains of PGPR and AMF in plant growth promotion, the mechanisms underlying these associations are not well understood at present. It is suggested that AMF acts as a vehicle for the bacteria [38–40], facilitating transferral between the roots. Further insight into the mechanisms of AMF-PGPR interactions should facilitate the development of optimized mixed inocula that can be used efficiently as tools for increasing crop yield.

N2-fixing bacteria improve the bioavailability of N to plants that may be further enhanced when plants are also colonized by AMF [41]. In terms of N_2-fixing rhizobia, mycorrhizal and root nodule symbioses are typically synergistic, both with regard to infection rate and impact on mineral nutrition and growth of plants. One possible explanation for the increased N_2 fixation in plants colonized by AMF is that when both N and P are limiting, AMF improves P uptake by the plant, leading to more available energy for N fixation by the rhizobia [42,43]. Moreover, recent studies have shown that specific AMF can use decomposing organic N sources for their own nutritional demands and growth, thus acting as potential N competitors of associative plants [44].

Considering the importance of host plant P status on AM symbiosis, P fertilizers may have a strong effect on the association between plants and AMF [29]. In intensive conventional farming systems, application of P fertilizer may lead to surplus of P that largely exceeds crop need, resulting in accumulation of total and bioavailable P in the soil [45–48]. This may lead to less reliance of plants on AM symbiosis, and consequently, lower colonization levels and propagule sizes [29]. Severe effects of N-based mineral fertilizer on AM colonization have additionally been reported [49–52], inconsistent with other findings [53,54]. However, organic nutrient sources, such as those applied in organic farming, are reported to stimulate AMF [49,55–62], further emphasizing the importance of maintaining a healthy soil microbial community. The issue of whether specific indigenous microorganisms should be selectively stimulated in soil or selected microbial strains added in the form of mixed inocula to large-scale crop fields remains to be established.

4. Animal Waste—A Farm Resource

Prior to the technological advances during World War II, most farmers used an organic way of producing their crops. However, the new possibilities to use large-scale irrigation, inorganic fertilizers and chemical pesticides resulted in a growing interest in chemical rather than organic farming. This kind of intensive agriculture has certainly increased crop yields but meanwhile implied significant environmental problems [22,63]. Moreover, mineral fertilizers and chemical pesticides tend to be more energy-consuming than organic products (Table 1). Consequently, increasing numbers of farmers are once again becoming conscious that animal waste produced on the farm can be of significant value. It is widespread practice for organic crop and animal farmers to cooperate, providing each other with straw, animal feed and manure to increase crop yield. Farmyard manure application, one of the most common strategies used by organic farmers to increase and maintain soil fertility [64], mainly acts as an important soil nitrogen source, and significantly contributes to nitrate and phosphorus leaching if not applied appropriately [65]. Since manure contains lower amounts of easily available nutrients than mineral fertilizers and differs between distinct animal types, farms and years, it is more difficult to calculate the appropriate application amounts and rates [65]. In order to minimize risks with nutrient leaching and to maximize plant uptake it is important to evaluate the rate and timing of manure land application. Which method to use and when to apply the manure depend on several factors, including cropping and managment systems, climate, type of animal waste and equipments used. In cropping systems it is important to apply the manure when the nutrients can be optimally used by the crops, which is often immediately before planting or sowing [65]. Leaching of nutrients is also depending on the time interval between fertilizer application and the first rainfall. Smith *et al*. [66] found that one week was sufficient for minimizing risk of leaching when swine and poultry manure was applied to soil. Different application techniques can affect the nutrient efficiency, such as different injection methods which minimize emission of ammonia [67].

A long-term field trial in Switzerland showed that after 21 years, the soil was positively affected by manure amendment, with increased biomass and microbial activities in organic systems, supporting the theory of increased nutrient turnover rates in organic farming [64]. However, while animal manure may be a suitable fertilizer, it is extremely important that care is taken to avoid soil and plant contamination with human pathogenic bacteria often present in untreated manure [68]. Adequate composting techniques for animal manure present an effective way of reducing high levels of human pathogenic bacteria [69]. One should also consider that specific bacterial strains, for example, *E. coli* O157:H7, remain longer in manure than in live animals, and thus, insufficiently treated manure is a potential source of reinfection of livestock with pathogens [70]. Consequently, proper composting procedures should be carefully optimized according to both duration and internal conditions within the pile. Manure is an important source of organic matter and nutrients, especially in organic farming where mineral fertilizers are not allowed. The risk for human pathogenic bacterial contamination of plants is highest where the produce is likely to be eaten raw (such as in the case of salads, fruit, spinach, and various vegetables) [71], but should also be taken into consideration for other types of crops where the risks are less well investigated. Previously, we examined the ability of Salmonella and *Campylobacter* strains to persist in manure and soil and disseminate to spinach plants. In many cases, the pathogens spread from manure to roots, and the pathogenic bacterial content in soil and on spinach leaves remained relatively constant during the entire evaluation period of 21 days [72,73]. On the other hand, other studies have shown a progressive decline of pathogenic bacteria, including Escherichia coli populations, in soil and manure [74]. Semenov *et al*. [75] demonstrated that the temperature conditions affect the survival of *E. coli* O157:H7 in manure, with lower survival under fluctuating than constant temperatures. In leafy vegetable crops, such as spinach and lettuce, the edible parts come in direct contact with the soil, thus presenting a significant risk for potential contamination. For example, organically produced lettuce was previously associated with two outbreaks of *Escherichia coli* O157:H7, probably contaminated through cow manure [76]. Organically managed soil is traditionally associated with higher biodiversity, compared to conventionally managed soil, and ecosystems with more diverse microbial communities are more resistant to perturbations [77]. This means that organic crops are less susceptible to infection by human pathogenic bacteria introduced in the manure, compared to conventional agricultural systems [78,79] to which chemical pesticides and mineral fertilizers have been added. Moreover, natural soil processes, including symbiotic relationships, local decomposition processes and nitrogen fixation can be disturbed by also other types of invasive microorganisms, potentially posing a threat against the stability of the ecosystem [80].

5. Green Manure and Cover Crops—Recycling of Plant Material

Cover crops are plants grown in high numbers to protect the soil, thereby minimizing leaching of nutrients. Legumes employed as cover crops can be used to fix nitrogen together with rhizobium bacteria, increasing the available soil N for adjacent plants [81]. Cover crops tilled into the soil function as green manure, and additionally minimize soil erosion and retention of soil moisture, leaving less space for weeds if maintained all season and improving soil structure [82]. The use of cover crops have been shown to increase the amount of soil organic C in rye and vetch/rye systems [83] and affect the nitrogen content and yield of maize [84]. However these effects can vary depending on the choice of cover crop [85]. For example, beneficial effects on soil organic matter content, a higher microbial respiration and microbial biomass were detected in a vineyard experiment in California [86]. One limitation of cover crops is the need for increased irrigation, which is a particular problem in dry areas [82]. The effects of green manure on nitrogen accumulation are usually highest on loamy soils due to their fertile, moist and nutrient-rich nature [87]. An Irish study has shown that upon growth of a combination of mustard cover crop with spring barley, the soil solution concentration of NO3 was between 38 and 70% lower than that without cover crop. Moreover, the total N content lost over winter was between 18 and 83% lower in the presence of cover crops [88]. Tonitto *et al.* [89] performed a metastudy comprising several studies that compared conventional N fertilization with cover crops in terms of crop yield, nitrate leaching and soil nitrate. When legume cover crops were used (with no mineral N added), yields were around 10% lower, compared to that in conventional systems with mineral N fertilization, but with 40% reduction in nitrate leaching on average. Non-legume cover crops with mineral N amendment showed no decrease in crop yield and 70% reduction in nitrate leaching. These findings suggest that diversified crop rotation using cover crops can be used to reduce N-leaching while maintaining acceptable crop yields [89]. However, the results may depend on several factors, such as type of irrigation [90], climate and soil [87]. In view of these complex interactions, it is important to investigate each situation and determine the most suitable combination for each climate, crop and cover plant.

6. Conclusions and Proposals

The main difference in energy and nutrient requirements between organic and conventional farming is the use of chemical fertilizers and pesticides in the latter system. Organic crop yields are often but not always smaller than conventional yields, and may be optimized using accurate fertilization regimes adjusted for each specific site, crop and type of fertilizer. The timing and rate of manure application is crucial to avoid unnecessary nutrient leaching and use of beneficial microorganisms to enhance plant nutrient uptake is another way of minimizing environmental damage by nutrient leaching and run-off loss. Cover crops are also employed to decrease leaching of nutrients and function as green manure if tilled into the soil, but an effective cover crop must be evaluated in advance together with the economic crop on the farm site. Recycling of on-farm manure is an effective way of utilizing energy and nutrients that would otherwise be wasted, but must be performed with care, since pathogenic bacteria could disseminate into the environment or crops if not handled properly. An efficient way of reducing the amount of pathogenic bacteria is to compost manure. In the future, energy-efficient agriculture may be achieved by integrating the organic and conventional farming forms. On-farm biogas plants are available to further decrease farm dependence on fossil fuels, even if this requires considerable funding and technical skills. Combination of small amounts of mineral fertilizer, where necessary, with the use of beneficial microorganisms to increase nutrient uptake could aid in optimizing crop yield without significant consumption of the available environmental resources.

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