Abstract. A growing demand for organic produce creates a demand for technologies that facilitate organic farming, also called ecological agriculture, without compromising on its standards. Organic farming and local food production involving the use of recycled inputs could increase as a consequence of an increase in fuel, transportation and food prices. Technological advances would allow for more efficient soil nutrient management and economical weed control in organic systems. In the case of organic – therefore free range animal production, they can help prevent nitrogen leaching from pastures, manage animals humanely, and closely monitor animal health. These technologies will need to meet constraints such as economically justifiable capital and operating costs, the use of renewable energy and high energy efficiency, minimum time and labor inputs, animal welfare and ecological sustainability. Such technologies, such as robotic weeder, software for soil nutrient management, and animal feeders are being developed in a few institutes throughout the world. This review briefly defines organic plant and animal production and discusses the technologies relevant to these operations, whether they were specifically developed for organic farming or may be adapted to it. The review concludes with the fact that technologies addressing isolated problems have been developed, but none provide a systems approach to improving the sustainability and feasibility of organic farming. There is therefore potential in pooling existing tools in a management system for managing ecological agriculture (organic farming). There are also existing tools that can be adapted to organic farming. Semi-autonomous robots could be developed as an alternative to the more complex autonomous ones. They would require an operator but their job would be of higher quality and comfort than that of current unskilled labor in agriculture.
Keywords. Organic farming, ecological agriculture, autonomous, semi-autonomous, software, weed management, nutrient management, labor, ergonomics, free range, GPS, zigbee.
**Explaining “organic”**

Organic agriculture is a management system that enhances the agro ecosystem’s function through agronomic, biological, and other cultural practices, and is considered less resource-intensive than traditional agriculture (FAO, 1999). Organic production builds on a systems approach requiring a close connection from the extraction of the raw material to the disposal of the end product. Under this whole time horizon, it is the goal to use minimum irreplaceable resources and rest products should be reused or disposed off without inflicting on the environment. The energy consumed during extraction, during operational lifetime and during disposal should be minimized and to the largest extent originate from renewable energy sources.

According to a FAO Organic Agriculture and Food Security report on organic farms (2006), the stability of organic agro ecosystems is sustained by increasing soil organic matter and microbial biomass. IFOAM, state authorities and the joint FAO/WHO food standards program started by the UN in 2001 (the Codex Alimentarius Commission) in 2001 have finalized a set of standards for the production, processing, labeling, and marketing of organic food (Hermansen et al., 2005).

The advantages of organic plant production, according to Mader et al. (2002) are an improved soil fertility and higher biodiversity. The latter were considered the reason for the lesser dependence of these systems on external inputs, as shown in the results of a 21-year study showing a 20% lower yield in organic systems, although input of fertilizer and energy was reduced by 34 to 53% and pesticide input by 97%.

Animal organic production is supported by a highly biological soil as well, and includes methods that are thought to enhance animal welfare. According to Hermansen et al. (2005), less metabolic disorders and higher feed consumption were observed in the organic than conventional systems. The environmental load of organic systems compared to conventional livestock production has the potential to be low, but fulfilling this potential requires better defined rules on animal stocking rates in organic systems. Organic production guidelines (Codex and IFOAM) state that the animals should be allowed to graze, weaning does not happen as early as in conventional farming (40 days for pigs), roughage should be at least 60% of the total dry matter intake, only feeds on a ‘positive list’ are allowed, synthetic, chemical solvents-derived or GMO-derived proteins are not allowed and preventive veterinary treatments are not allowed except for some preventive antibiotics, coccidiostats and anthelmintics. Free-range is therefore implied in organic and it addresses animal welfare issues, which inspired the European commission (2008) to ban the use of battery cages for laying hens starting 2012. A study by the European Food Safety Authority (EFSA, 2004) showed that keeping laying hens in battery cages increased the risk of disease, bone breakage, harmful pecking, behavioral problems and mortality. The alternative is enriched cages (750 cm² per hen, and contain a nest, litter, perch and clawing-board) or systems such as barns or free range. Free-range also addresses ethical concerns relating to animal welfare which influence consumers of organic foods (Harper and Makatouni, 2002).

Organic aquaculture has standards developed by Germany's Naturland, the UK's Soil Association, Sweden's KRAV standards and IFOAM. The same as terrestrial animal production applies, including protecting the welfare of animals and not destabilizing surrounding ecosystems, both aquatic and terrestrial. This creates an additional challenge in the case of fish ponds and other bodies of water that are in contact with the environment (Brister and Kapuscinski, 2000).
How is ecological agriculture (organic farming) pertinent to today’s food production?

Less dependence on external inputs, and providing an outlet for recycled organic waste, makes organic farming a good choice for local production, especially as the cost of fossil fuel increases, and with is the cost of transportation, and fossil fuel-based synthetic inputs. The FAO Organic Agriculture and Food Security report (2006) states that organic agriculture can address local and global food security challenges. It is not a niche market since it is practiced in 120 countries, covering 31 million hectares of cultivated land plus 62 million hectares of certified wild harvested areas. The organic market was worth US$40 billion in 2006, and expected to reach US$70 billion by 2012.

The need for technologies

Increasing organic farming efficiency and yields would allow meeting the market demand while maintaining organic standards (USDA Economic Research Service, 2000). There were in 1998 300,000 fewer small farms in the US than in 1979, a trend that could be reversed by more efficient and economically sustainable organic farming (USDA, 1998). High managerial costs are the overall issue discouraging conversion to organic systems (USDA, 2001), even though organic produce is one of the fastest growing segments of the food industry, with sales totaling $7.8 billion in 2000 (USDA, 2001). These include labor costs, since labor substitutes for the chemical suppression of herbicides and certain pests. Factors like age of farmer, type of farm, soil type, and economical constraints, are also determining the rate of conversion and illustrate the importance of an in-depth analysis of the actual factors determining the potential conversion, and using this information to make better informed evaluations of the development of organic farming.

Organic systems rely on organic matter amendments from which a small fraction of nitrogen mineralizes over the years. This implies that models need to be developed for nutrient management specific to organic farming, for the efficient use of soil nutrients and to manage nitrogen mineralization as to avoid high soil amendments costs, which limit organic farming adoption. Resources available today to organic farmers prescribe for the most part cultural practices, and relatively few mechanical, automation and software solutions. More of such technologies could be developed to support the tenets of organic farming: maintaining a high biological activity in the soil and eliminating non-target effects of synthetic inputs, while reducing labor and other costs.

In animal farming, such as free-range pigs, outdoor rearing creates a risk of nitrogen leaching if animal waste is not evenly spatially distributed over pastures, a risk that negates the ecological advantage of organic animal production. A closer management of animal feeding and health care is also needed to ensure that these operations are ecologically sound as well as humane to animals (Hermansen et al., 2005).

Constraints that the technologies must meet

The continued development of organic farming means that increasingly new technologies are introduced to the organic farming principle (Sørensen, 2001). This is a result of the increasing professionalism, specialization and introduction of rational productions methods in organic farming (e.g. Andreasen, 2001; Christensen & Frandsen, 2001), which causes considering the potential of the technologies as an integrated part of the organic production platform.

The essential question is how organic technology can be adopted and evaluated based on the organic concept. In the course of the last 30-40 years, the technology development within
conventional agriculture has been based on the premise of achieving reduced costs by using more effective machines and technology for animal housing (Christensen, 2000). In organic farming, technology evaluation must be system oriented and be based on a number of factors related to sustainability. The constraints and objectives to be met include:

- ensure quality in products (minimal change in the product during processing)
- ensure quality in work processes (working environment)
- ensure communication of the organic status to consumers
- ensure minimization of the fossil energy sources
- the technology must not be just information, but a tool to implement it in a practical manner
- capital cost: investment must be justified by reduced costs in labor and neglected task
- operating cost: justified by returns and saved labor costs
- energy efficient
- uses renewable resources or recycled material if possible
- low time and labor inputs
- low weight, to avoid soil compaction, high porosity needed to support high root growth in plant, and aerobic animal waste degradation in free range
- small size, to fit intensive agriculture plots. The GreenTrac for example, a tool carrier developed for organic outdoor gardeners, has the issue of being too big for many tasks (Sørensen and Frederiksen, 2002).

The above lists some the factors which must be included when carrying an organic technology evaluation. Technology comprises both the physical technique and the conditions surrounding its usage (Technology council, 2001). For example, the physical technique comprise machines, buildings and computers, while conditions around the usage of the technique include provisions, standards, methods, work organisation, values, ethics, etc. In agriculture, the employed technologies form a system, where each technology does not only enable a given operation, but must be viewed as part of a set of technologies and methods. Methods and technologies, together, form an agricultural technology (Grigg, 1974) and this approach to technology is especially important in an organic setting.

Technologies that address some of the challenges in organic farming

 Soil nutrient management

Fertilizing strategies affect both yield and the environment, now that fewer organic operations have an integrated production involving both plants and animals. The supply of nitrogen is limited since in organic soil amendments most of the nitrogen is in the immobilized form. Watson et al. (2002) reports that unlike short term and also targeted strategies in conventional agriculture, successful soil nutrient management in organic farming can only be the results of long-term integrated approach, where interactions of components of an organic system are accounted for.

According to Pang and Letey (2000), the challenge is to synchronize the rate of nitrogen mineralization from organic matter with plant N demand, especially in the case of crops such as corn which has a high maximum N demand. A large amount of unprocessed organic waste
would need to be applied in order to meet high N-uptake in crops such as corn (relative to wheat). This would lead to high mineralization and leaching in subsequent years.

Koopmans and Jan Bokhorst (2002) describes the NDICEA model (Nitrogen Dynamics in Crop rotations in Ecological Agriculture), a mechanistic model which calculates changes over time of soil water; soil carbon; soil organic matter, soil organic and inorganic nitrogen, all for each soil layer, over the course of a crop rotation and in 1 week increments. When tested the model had a fit of $R^2 = 0.65$. The nitrogen release rates from organic fertilizers predicted by a model developed by Van der Burgt et al. (2006) also have a close fit with measured values.

In a study by the Technical Institute for Organic Farming in France (ITAB), Nicolardot (2007) proposed a decision-making tool to manage fertilization in organic farming; the "FERTIAGRIBIO" software. This software is dedicated to organic systems, which unlike conventional agriculture have diversified cropping systems and nutrients that mineralize from organic matter over long term, as opposed to readily available synthetic nutrients. Outputs from this program can be used as nitrogen inputs in yield-predicting programs for organic systems, such as AZODYN-org and STICS. The program manages nitrogen resources including nitrogen availability as a function of previous leguminous crops, intercrops and organic amendments.

The nitrogen mineralization rate of unprocessed waste can be increased by amending the soil with earthworms, which break down organic matter through a grinding action in the gut (Edwards, 1995). Nitrogen release for organic matter processed by earthworms is also slower, and therefore more in sync with nutrient uptake rate, relative to soil amended with compost or synthetic fertilizers (Chaoui et al., 2003). No model was found to determine amendment rates of earthworm in function of soil condition, crops and time.

**Controlling weeds and pests**

Bårberi (2002) reported that manual weeding is successful only if combined with a program of preventive measures such as crop rotations, cover crops and practices to increase crop competitiveness against weeds. These include precision-fertilizing and irrigation, transplanting as opposed to seeding, specific crop rotations, and a combination of preventive measures. The premise of managing weeds should be knowledge of both weed and crop ecology in each agro-ecosystem, and the influence of the cropping system on weed population dynamics.

Weeds are a main source of cost in plant production. According to Jørgensen et al (2006), the costs are in terms of labor, tasks neglected in favor of weeding, or yield decrease due to insufficient weeding in case labor is not always available. In example, the repetitive task of manual weeding in Denmark is done while standing, using a hoe, by kneeling, or while lying on a trailer, all of which are strenuous positions and a repetitive task. Danish outdoor gardeners use 50-300 hours per hectare for manual weeding in intensive agriculture (Ørum and Christensen, 2001; Melander and Rasmussen, 2001).

Parish (1990) listed eco-friendly weeding methods, including destroying weeds by heat (torching or steaming), by blocking off-light (covering the plants), mechanical weeding, and solarization to kill off plant seeds in the soil. Hewson and Roberts (1971) reported that the critical period for weeding is 4 – 10 weeks after 50% plant emergence (Figure 1).
Weed management software

There is no weed management software dedicated to organic farming, prescribing non-chemical weed control methods, or accounting for the interaction between crop rotation and weed ecology over the season.

Neeser et al. (2004) developed a program, Weedsoft®, to identify weeds and create an environment-friendly plan to control them. However this plan includes herbicide use.

Automated weeding

In the Netherlands, emphasis is placed on improving manual weed control for use in organic farming by developing torsion and finger weeders, and sensor-aided weeding (Kurstjens et al., 2000). However, as Bàrberi (2002) reports, torsion weeders eliminate inter but not intra row weeds.

Lukas, A weeding robot at Halstad University in Sweden (Figure 2) weeds within sugar beet rows (Åstrand and Baerveldt, 2002), and it recognizes its path through infrared cameras and machine vision.

HortiBot (Figure 3), a plant nursing robot (Jørgensen et al., 2006) was created by accessorizing with a kitSpider ILD01, a slope mower for the maintenance of uneven terrain at up to 40
degrees slopes (Dvořák Machine Division, Czech Republic). The modifications included individual controllable wheel modules and a lift arm with a control module. The engine is also coupled with a control module and a central Hortibot Control Computer (HCC) has been mounted. The vision for the Hortibot is a tool carrier for high-tech plant nursing, to be used in organic vegetables production among others. This tool might be implemented in the future with high-tech tools for weeding including laser and mechanical devices. The functionalities include the capability of traversing over several parcels with visible rows autonomously based on a new commercial row detection system from Eco-Dan with minimum use of Global Positioning Systems (GPS).

Feasibility studies have shown a considerable increase in profitability (75-80%) when introducing a weeding robot into organic horticulture (Sørensen et al, 2005).

Transplanting

Transplanting seedlings increases a crop’s competitiveness with weeds, relative to direct seeding. A melon harvester was modified into an automated transplanter (Edan and Bechar, 1998). A gripper using a grasping force of 1.5 - 2 kg successfully pulled seedlings out of a tray and deposited them in a hole created by an accompanying implement. Graphic simulation was used to optimize the gripper’s actuator speed and the seedling tray location and design, in order to obtain minimal cycle time. The gripper was tested on lettuce, tomatoes and celery seedlings with an overall transplanting success rate of 92%. The vehicle’s path was determined by analyzing the categories of a colored image; sky, path and trees, for their color, intensity, shape and size. An algorithm then determined the midway curve of the path, along with safety margins.

Nagasaka et al. (2004) developed the prototype of an autonomous 6-row rice seedlings transplanter (Figure 4). The controller of the transplanter is programmed to calculate its position in the field through real-time kinematic GPS coordinates, and its direction based on data from a fiber optic gyroscope. The controller is connected to actuators which control steering, engine power, brake, and the position and operation of the implement. The vehicle deviated from the
planned path by 12 cm at the most. This was a good enough precision for transplanting, but not for weeding. The transplanter completed its operation over a 10 m by 50 m field in 15 min.

Figure 4. Rice seedling transplanter (Nagasaka et al., 2004). Photo credit: precisionpays.com.

Feeding animals in free-range operations

In animal production, delivering supplemental feed to free-range animals increases labor cost, particularly during plant dormancy. Free-range animal production also poses a risk of nitrogen leaching if waste is not uniformly distributed in the field (Hermansen et al., 2005). This results from animals not rotating across pastures, furrowing consistently in the same area and resulting in degradation of the soil surface (especially during plant dormancy), erosion, and leaching.

An automated feeder (Jørgensen et al., 2007) that allows rotating the location of animal feed would guide animals to rotate over the pasture, in pursuit of the feed source (Figure 5). It also reduces the labor cost of delivering feed in free-range operations. It carries feed to free range animals in the field, and tests have shown the animals respond positively to its presence. The automated feeder is one variant of a “working ant robot” (Jørgensen et al., 2007). It is a solar powered and potentially autonomous vehicle when combined with local positioning system and a simple farm design.

Figure 5. Automated mobile pig feeder (Jørgensen et al, 2007).

Housing and milking in free-range operations
Housing of free-range animals can be either ambulant or fixed. In the case of free range chicken, ‘eggmobiles’ are commercially available (Figure 6). Outdoor small size shelters are also scattered throughout the grazing range of free-range pigs used for free-range pigs. This poses a challenge because of the cost of labor, and the task of bringing free-range cows to the milking parlor. Fresno dairyman Mark McAfee used mobile milking parlors, to help create a “pro-cow” environment (Hamilton, 2003).

Figure 6. Eggmobile. Picture credit: Debbie Roos, North Carolina- Cooperative extension.

Integrated animal and feed production results in the most energy and cost efficient animal rearing. Andersen (2008) describes an envisioned diversified seasonal multi-functional agro-forestry system (Figure 7) where small raised fields (for better drainage) are cultivated and are interspaced by meadows, forests and hedges. Small barns would be located close to the cultivated fields to reduce transportation cost of feed and waste. An ‘ant’, a small and light solar powered autonomous vehicle would maintain this operation by spreading soil amendments, sowing seeds, harvesting cereals and cutting straw to deliver to animals.

Figure 7. Envisioned diversified organic production maintained by ‘working ants’ (robots), adapted from Fig. 1. in Andersen et al. (2008).

**Rotating animals in pastures**

An alternative to fences and rotating cows by handling them would improve animal welfare compared to rounding up animals in a rushed manner, allow for more even grazing and less soil degradation, and eliminate fence costs. Anderson (2007) developed a humane method to guide cows to given regions of a pasture, along with sheep that were bred to bond with and follow cows, to be protected from sheep predators. A GPS-equipped cow collar with radio emitter (Figure 8) emits cues, when the cow is moving (and not in an attempt to move it by force), to direct the animal in the direction. Cues were emitted in response to spatial data analysis of the cow’s GPS position. In a study by Butler et al. (2008) a “Smart Collar” for cows was equipped with GPS and a position-aware computer which applies a stimulus to the animal in response to its location relative to a virtual fence line that can be dynamic.
Repelling predators and managing water quality in aquaculture

Birds are predators in organic and conventional aquaculture. They can cause high fish losses and reduce the sustainability of these productions. Conventional control methods include poisons, sonic canons and shooting; which can be ineffective and is not ecologically sound in the case of endangered bird species (Hall et al., 2005). An alternative is a semi-autonomous vehicle (boat) that repels birds by the eco-friendly method of shooting at them with a water gun also known as a ‘scarebot’ (Figure 9; Hall et al., 2005). The vehicle is solar powered and was programmed in 2005 to randomly navigate the surface of fish ponds. The vehicle can also be equipped with a dissolved oxygen sensor and a module for aerating ponds. This solution reduces fossil fuel use and pollution, death of birds, eliminates toxic cumbersome (nets) or sound-polluting pest control techniques. It also eliminates the need for human riders in boats and planes: an underpaid job and unsafe job.

Strenuous labor

Musculoskeletal Disorders (MSDs) are common in labor intensive agriculture, as reported by Barret and Fathallah (2001), who evaluated weight transfer devices such as the Happyback, based among others on the activity (emg) of the spinal and stomach muscles. Some devices reduced back activity but increased the load on the knees and leg. Yonetak and Toyama (2005) from the Tokyo University of Agriculture and Technology developed a suit, reported in the news as “wearable farming robot suit” (Figure 10), which reduces the load placed on the worker’s joints and muscles. Sensors in the suit detect muscle activity and amplify the user’s movement through motors placed close to the joints.
Tools that could be incorporated in future technologies for organic farming

Remote control

Remote control is one such tool that can be incorporated in future technologies for organic farming. Gomide et al (2001) tested a system for acquiring data into a laptop and controlling the operations of a crop production through a mobile laboratory, using wireless ethernet connections. This could be applied to create semi-autonomous tools operated remotely. Such a tool will require less development than a fully autonomous one, while increasing the job quality of the worker, such as in the case of remotely controlled weeding.

Precision agriculture

Affordable precision agriculture fits in this category as well, as potentially made possible by a low cost Zigbee network of wireless nodes. Zigbee was developed for the remote control of electronic devices, and has applications in precision agriculture (Hebel, 2006). It has among others been used for remote sensing in viticulture (Morais et al., 2008). Zigbee is a mesh network which eliminates the need for a central receiver. Instead less powerful and cheaper nodes (with a limited range) relay a signal to each other until it reaches its prescribed destination (receiver). Zigbee routers are programmed to relay data along the shortest path, determined on demand through the Ad-hoc On Demand Distance Vector algorithm. It has a transmission range of 10-75 m. An alkaline battery can power a node for one to two years. A zigbee node is a radio and microcontroller, typically on one chip. It requires a voltage of 2.0 to 3.4 V, transmits data at 250 kbps and has 3 Power Modes: less than 1 µA Off Current, 3.0 µA in hibernation mode and 40 µA Typical Doze Current.

Positioning systems

Affordable positioning systems can also be used to support organic farming, such as Local Positioning Systems (LPS) (Bulusu et al., 2000) instead of Global Positioning Systems (GPS). In a study by Søgaard (1999), a local positioning system employs a rotating laser emitter and an electro-optic sensor on a moving vehicle, which detects the same laser beam it emitted once it is deflected by a set of laser deflectors with known locations in the field. The rotating laser emitter has a known velocity, used along with the timing of laser deflection, and the deflector’s position to derive the angles formed between the lines connecting the deflectors to vehicle, at any given position. The vehicle’s position is extrapolated in real time, by triangulation.
Le (2008) at Texas Instruments describes potential localization capacities of Zigbee nodes. A System-on-Chip (SoC) would be attached to Zigbee blind nodes (nodes which do not know their position). This chip contains an algorithm that calculates the blind node’s position based on the strength and the radio signal it receives from several reference nodes (to account for radio signal variability due to the environment). Reference Zigbee nodes have a known position and can be a fraction of the nodes used in an area, equally spaced among the other nodes.

Zigbee nodes with localization capacities could be used to allow plant and soil sensors to relay data including their location. The data can be used by an autonomous implement to reach the plant or soil area that “called”, as opposed to relying on machine vision to detect the spot in the field in need of maintenance. The challenge remains the cost of installing the sensors, or possibly attaching them to seedlings before transplanting.

**Animals as biosensors**

Allowing animals to become biosensors and actuators is another possible technological advance in organic farming. In a study by Puppe et al. (2007), pigs were trained to recognize that a sound cue indicated a change in the location of their feeding station, and to push a button for food. Similarly animals could be trained and equipped to respond to a need by triggering a device that would address that need. This could help create an optimal environment for animal growth, and possibly limit environmental damage in animal operations.

**In-house manufacturing**

The affordable production of parts, such components of locally produced semi-automated tools, could be made possible by devices such as the 3D printer developed at Bath University, UK (Malone and Lipson, 2007). Also known as the Rapid Replicator or Reprap (Figure 11), it is an affordable tool for replicating 3D parts, if not precision-designed. It was recently successfully used to produce most of the parts needed to assemble a replica of itself.

![Figure 11. A 3D-printer developed at Bath University. Photo credit: www.reprap.org.](image)

**Online tools**

Some tools can be used to put knowledge into practice, such as for example a comprehensive online freeware (and expandable database) for finding biocontrol agents, weeding techniques, crop rotations and other practices. Another tool to rapidly expand knowledge is the use of a populist approach such as the wiki system, where researchers and producers would be both readers and contributors. This is expected to allow faster expansion of scientific and practical knowledge.

**Conclusion**

In conclusion, some innovative advances were found such as software for nutrient and weed management, autonomous weeding, transplanting, and free-range animal feeding and herding, either dedicated to or applicable to ecological agriculture (organic farming). Along with the latter, existing mesh sensors, remote control technologies, and known abilities of animals to use tools,
could be incorporated to design ecological plant and animal production systems. Also each of
the existing technologies listed in this review address a separate need in organic farming each,
which hints at the potential of using these solutions to design a comprehensive system for
managing organic production. The limited number of autonomous robots in this review also
indicates the long development time and other complications involved in creating these tools.
Semiautonomous robots might be the alternative that allows for quicker development of
technologies that make organic production more convenient, while replacing inconvenient
unskilled labor jobs in organic farming with jobs where operators remotely control semi-
autonomous robots from a comfortable setting. Overall this review suggests that some research
and development activity has targeted the advance organic farming, and if further pursued it has
the potential to allow ecological agriculture (organic farming) to meet the increasing market
demand on organic products without compromising the standards that define organic systems.

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