Organic Production of Strawberries

Focus on practical applications

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Abstract

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Organic fruit and vegetable growing is increasing world-wide, but knowledge concerning best practice is generally empirical rather than field-based. This thesis extends knowledge concerning best practice in Swedish organic strawberry (*Fragaria x ananassa* (Duch)) production, which is usually based on a two-year crop.

A series of four field experiments were conducted at Rånna Experimental Station (58°27'N, 13°51'E) on the strawberry cultivars 'Honeoye', 'Cavendish' and 'Korona'. Specific objectives were to investigate: the effects of different organic fertilisers combined with degradable plastic mulch on plant establishment, yield and nitrogen mineralisation in soil; the efficiency of biological pest control using a predatory mite against strawberry mites (*Phytonemus pallidus*); innate within-field dispersal capacity of strawberry mite; the effects of pyrethrum combined with fleece covering on damage by strawberry blossom weevil (*Anthonomus rubi*).

Plant establishment measured as fruit yield was improved by 60% when degradable plastic mulch was used, probably through more flowers being initiated. Additional applications of organic fertiliser during the cropping period had little effect on yield.

Biological control using the predatory mite *Neoseiulus cucumeris* reduced strawberry mite populations by up to 50% but there was no increase in yield. It was difficult to draw clear conclusions from the strawberry mite dispersal pilot study, but mites tended to move more easily along planted rows than between rows.

Pyrethrum alone had no visible effect on flower bud damage by strawberry blossom weevil but when combined with fleece covering it reduced the number of 'Honeoye' buds damaged by weevils by approximately 10%. This was followed by a corresponding increase in cultivar yield. Similar effects were not recorded in the other cultivar examined.

The study identified the following practical consequences for organic strawberry production:

- Choice of pest-resistant cultivars is extremely important for success.
- Use of clean plants and an efficient predatory species is essential in controlling mite infestations.
- Use of degradable plastic mulching is recommended.
- Fleece covering is recommended for protecting some cultivars against strawberry blossom weevils.
- Only an initial starter fertilisation is required.
- Use of pyrethrum is not recommended.

Keywords: *Fragaria* × *ananassa* Duch., organic fertiliser, strawberry blossom weevil, strawberry mite, biological control, degradable plastic mulch, fleece cover, plant extract.

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Appendix

Papers I-IV

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.

I. Berglund, R., Svensson, B. & Gertsson, U. 2006. Impact of plastic mulch and poultry manure on plant establishment in organic strawberry production. *Journal of Plant Nutrition 29*, 103-112.

II. Berglund, R., Svensson, B. & Gertsson, U. 2007. Nitrogen availability, plant growth and yield in strawberry production with organic fertilizers and plastic mulch. *Biological Agriculture and Horticulture.* Accepted for publication.

III. Berglund, R., Svensson, B. & Nilsson, C. 2007. Evaluation of methods to control *Phytonemus pallidus* and *Anthonomus rubi* in organic strawberry production. *Journal of Applied Entomology*. In press.

IV. Berglund, R., Svensson, B. & Nilsson, C. Dispersal of *Phytonemus pallidus* (Acari: Tarsonemidae) within and between rows in a strawberry field. *Manuscript.*

Aims and objectives

The aim of this doctoral thesis was to study the impact of different cultivation practices on organic production of strawberries. The main emphasis of the study was on plant establishment, season nutrient supply and control strategies against two important pests, and possible side-effects and interactions of these treatments.

Specific objectives were to investigate:

- The effects of different organic starter fertilisers in combination with or without degradable plastic mulch on **plant establishment**, *i.e.* plant growth, yield and diseases in the first year of production.

- The effects of different organic fertilisers as nutrient supply during the **cropping period**, in combination with or without degradable plastic mulch, on plant growth, yield and diseases during two to three years of production.

- The effects of nutrient supply at **plant establishment** and during the **cropping period** in combination with or without degradable plastic mulch on the amount of mineralised nitrogen in the soil in fields with and without strawberry plants.

- Whether a biological **pest control strategy**, using the predatory mite *Neoseiulus cucumeris* could decrease the number of strawberry mites (*Phytonemus pallidus*) and increase fruit yields under field conditions.

- Whether a botanical **pest control strategy** using pyrethrum in combination with or without a physical **pest control strategy** based on fleece cover could decrease the damage caused by strawberry blossom weevil (*Anthonomus rubi*) and increase yield, and whether these methods affected number of strawberry mites and yield quality, *i.e.* disease incidence and fruit size.

- The innate **dispersal** capacity of the strawberry mite within a field.

Background

Organic production

The total area of certified organic agriculture is steadily increasing in the world. In 2000, less than 10 million hectares (ha) were organically farmed but by 2006 the figure had increased to more than 30 million ha. The ten countries with the highest percentage (5-25%) of land under certified organic management are European. However, the rapid development that started in Europe in the 1990s has slowed down, while in North America the trend is the opposite. There, the market for organic products is reporting the highest growth world-wide (Yussefi, 2006).

There are different definitions of organic agriculture. According to IFOAM (International Federation of Organic Agriculture Movement), a world-wide organisation with members from over 100 countries, organic agriculture is based on four principles (http://www.ifoam.org/about_ifoam/principles/index.html; 10-Feb-2007):

> "The principle of **health** – *Organic Agriculture should sustain and enhance the health of soil, plant, animal, human and planet as one and indivisible.*
>
> The principle of **ecology** – *Organic Agriculture should be based on living ecological systems and cycles, work with them, emulate them and help sustain them.*
>
> The principle of **fairness** – *Organic Agriculture should build on relationships that ensure fairness with regard to the common environment and life opportunities.*
>
> The principle of **care** – *Organic Agriculture should be managed in a precautionary and responsible manner to protect the health and well-being of current and future generations and the environment."*

Within the European Union a set of minimum requirements have been drawn up in order to meet these principles (EU Regulations 2092/91, 24 June 1991). At farm level these requirements imply that the fertility and the biological activity of the soil must be maintained or increased by *e.g.* cultivation of legumes, green manuring and/or use of farmyard manure. However, a few inorganic fertilisers listed in the EU regulations may be used when adequate nutrition of the crop is not possible by use of organic material. To control pests, diseases and weeds a combination of measures should be undertaken, *i.e.* choice of appropriate cultivars, mechanical cultivation practices and protection through natural enemies or releases of natural enemies. When there is an immediate threat to the crop, botanical products such as azadirachtin (from the Neem tree), pyrethrins (from *Chrysanthemum cinerariaefolium*) and certain microorganisms are permitted.

The regulations for organic production can be modified within the different EU member countries as long as these national regulations include all the minimum requirements stated by the European Union. Each country has its own inspection system and the labelling of the organic products must tell the consumer whether the product is approved by the European Union or by the country's national regulations. The current goal of the Swedish government is that 20% of the total cropping area in Sweden should be in certified organic production by 2010 (Anonymous, 2006).

Table 1. *Countries with the largest production of strawberries in each continent measured in Mt and the area harvested in 2005. Numbers from the Scandinavian countries are also included in the table (http://faostat.fao.org/site/567/default.aspx; 10-Feb-2007).*

	Production (Mt)	Area harvested (ha)	Yield (kg/ha)
The world	*3 661 464*	*257 127*	*14 240*
Australia (Oceania)	23 737	865	27 441
Chile (S. America)	25 600	1 020	25 098
Morocco (Africa)	106 100	2 780	38 165
Japan (Asia)	196 200	6 880	28 517
Republic of Korea (Asia)	200 000	7 000	28 571
Spain (Europe)	308 000	7 600	40 526
USA (N. America)	1 053 242	21 125	49 857
The Scandinavian countries			
Denmark	4 600	730	6 301
Norway	9 577	1 606	5 963
Sweden	10 168	2 139	4 754

Botanical background

There are approximately 20 different strawberry species and they belong to the botanical family *Rosaceae.* The commercially grown strawberries are cultivars of *Fragaria x ananassa* (Duch) or cultivars closely related to this hybrid. The hybrid originates from European horticulture in the 18th century as an accidental crossing between *F. virginiana and F. chiloensis*, species from the Americas. The commercial strawberries are mostly propagated from runners. *Fragaria x ananassa* is considered a quantitative short-day plant when grown at low temperatures (Vince-Prue, 1975). The development of vegetative runners is promoted by long days. However, modern breeding has developed day-neutral cultivars. The cultivars used in the following experiments were short-day cultivars.

Production of strawberries in general

Strawberries are produced all over the world. According to FAO statistics, 73 countries from all continents except Antarctica reported a production of strawberries in 2005 (http://faostat.fao.org/site/567/default.aspx; 10-Feb-2007). The largest producers of strawberries in the world measured in Mt are shown in Table 1. The country with the largest area harvested was Poland with 53 700 ha, producing 3348 kg/ha (not tabulated).

The most common way to produce strawberries is in the open, in matted rows or in annual hills, although greenhouses and plastic tunnels are also important in some parts of the world. The matted row system is the most dominant in climates with cold winters and short summers. In this system, both planted crowns and runners produce fruit. Straw mulch is used and irrigation is mostly by overhead sprinklers. In this system the plants are harvested over 3-5 seasons and the yield is mostly below 10 Mt/ha (Hancock, 1999b).

In the high-producing countries, which have mild winters and warm summers, annual hills is the dominant system, often in combination with plastic tunnels. In the annual hills system, the strawberries are planted in raised beds on plastic mulch with drip irrigation. In this system the planted crown produces the fruit and the runners are not allowed to establish. The plants are only harvested for 1-2 seasons and yields from day-neutral cultivars can exceed 30 Mt/ha per season (Hancock, 1999b).

Organic production of strawberries

Fertilisation strategies and mulching

Plant establishment

In organic production of strawberries, it is recommended that no more than two years of harvesting be carried out in the perennial matted row system. After more than two cropping seasons there tends to be a build-up of large populations of pests, diseases and weeds and using shorter rotations is one way to avoid this (Daugaard, 2000). However, with the two-year production strategy, rapid and successful plant establishment is very important.

Strawberries have a shallow root system and this makes the plants vulnerable to weed competition. A survey conducted among berry producers in Sweden showed that they rated weeding as the single biggest problem in the production (Rölin & Larsson, 2002). The importance of weed control has also been demonstrated by Pritts & Kelly (2001), who showed that newly planted strawberries were very sensitive to weed competition during the first 2 months and that uncontrolled weed growth during this period reduced fruit yield by 20-65%. The use of plastic mulch as a row covering is one way to avoid weeds. However, this method hinders runner rooting in consecutive years. The use of photodegradable black plastic could be an option since it controls weeds effectively during the important phase of establishment and then degrades, allowing runners to root. Black plastic also improves nutrient availability and affects soil temperature and moisture, which improves plant establishment and leads to increased total yields (Skroch & Shribbs, 1986; Wooldridge & Harris, 1991; Birkeland, Døving & Sønsteby, 2002; Plekhanova & Petrova, 2002).

Manures used as organic fertilisers may vary in nitrogen content and be difficult to spread evenly in the field. There are also fertilisers consisting of dried and pelleted manure that are homogeneous in nitrogen content and easy to spread evenly in the field. However, production of such fertilisers consumes a high amount of energy (Vestgöte, 2000) and the products should therefore be avoided in organic production. There are few scientific data from field experiments on fertilisation in organic strawberry production. In one experiment in the present investigation, fresh poultry manure was compared with dried and pelleted poultry manure.

Cropping period

A number of experiments on conventional production of strawberries focus on the amount of nitrogen used. Many of these studies show that more nitrogen leads to higher yields of fruit, but excessive amounts of nitrogen lead to no increase or even a decrease in yield (Albregts & Howard, 1986; Miner *et al.*, 1997; Gariglio, Pilatti & Baldi, 2000). Other experiments show no increase in yield with increased amounts of nitrogen (Darnell & Stutte, 2001). In our experiments on nutrient supply during the cropping period, a fixed amount of N was supplied in the form of different organic fertilisers in combination with or without plastic mulch. Strawberry yield is influenced by both the number of flower buds initiated in August to October of the year before harvest and the conditions during their development in the following season, and in our studies, fertilisers were applied to meet the plant requirements during these important periods. Since plastic mulch alters soil temperature and moisture, it was also important to investigate how this affected the amount of nitrogen from the different fertilisers mineralised in the soil.

Pest control strategies

Some cultivation practices are not specifically intended to control pests and diseases but have an indirect impact on population dynamics of the pests. Other practices are intended to control one pest but also have an effect on other organisms. These interactions are important to consider while planning production. Pests that are controlled simultaneously in conventional production may cause problems in an organic production system (Tuomo Tuovinen, pers. comm. 2002) and attention must be given to all relevant pests and diseases and the fact that few obstacles are solved simultaneously. To have a successful organic pest control strategy it is also essential to start with pest-free plant material from cultivars with high resistance to important pests and diseases. These preventive measures should be combined with short rotations to avoid large pest population build-ups.

Biology of the strawberry blossom weevil

The strawberry blossom weevil (*Anthonomus rubi* Herbst, Coleoptera: Curculionidae) is an important pest in both organic and conventional strawberry plantations. The adult weevil is 2-4 mm long, black with greyish pubescence and overwinters as an adult in or near the strawberry field (Figure 1). It appears in the field in April or May when the temperature exceeds 13-15 ºC. The first noticeable damage is small punctures in the leaves but this is of no significance to the plant. The main damage is made at ovipositioning. After the egg is deposited, in an unopened flower, the female cuts off the flower bud by making small punctures around the flower stalk (Figure 2). The damaged bud ceases to develop and

Figure 1-2. Adult strawberry blossom weevil (left) and damaged bud (right).
Photo: Tuomo Tuovinen.

withers, partly attached to the stalk, or falls to the ground. The larvae and pupae develop inside the bud and 4-5 weeks after ovipositioning the new generation of weevils appears (Alford, 1984). The number of buds attacked can be substantial, with 50% damaged buds (Simpson *et al.*, 1997). The population of overwintering weevils approximately doubles within two years (Aasen & Trandem, 2006) and one way to limit the population growth is to avoid fields adjacent to old fields with strawberries, raspberries or blackberries, since the weevil also attacks these species.

Biology of the strawberry mite

The strawberry mite (*Phytonemus pallidus* (Banks), Acari: Tarsonemidae) is a 0.25 mm long oval-shaped, pale brownish mite, which overwinters deep in the crowns of strawberry plants (Figure 3). It feeds on young leaves and the injection of toxic saliva probably causes the damage (Lindquist, 1986). Infested plants become stunted and the leaves become wrinkled and sometimes hairier (Figure 4). The developmental time for strawberry mites is highly temperature-dependent. Higher temperature decreases the time from egg to adult and increases oviposition rate (Easterbrook *et al.*, 2003). The plant symptoms appear late in the season since it is the youngest leaves that are attacked. The population peak is in August or September and large populations in the autumn may affect flower initiation and reduce yield in the following year (Stenseth & Nordby, 1976). Strawberry mites are often introduced to new plantations from transplants originating from infested fields. Within the field, the main dispersal is caused by adults crawling from plant to plant or on tiny runners (Alford, 1984).

It is suggested that the species *P. pallidus* may be a species-complex (Lindquist, 1986) consisting of three subspecies; *Tarsonemus pallidus pallidus* Banks (the cyclamen mite), *T. pallidus fragariae* Zimmerman (the strawberry mite) and *T. pallidus asteris* Karl (the aster mite). This might explain the different scientific names mentioned in the literature.

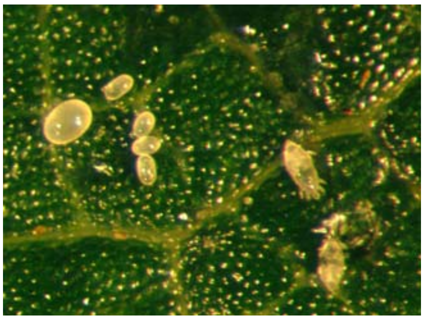
 

Figure 3-4. Phytonemus pallidus adults and eggs (left). There is also a large Phytoseiid egg to the left in the picture. Strawberry plant damaged by *P. pallidus (right).*
Photo: Tuomo Tuovinen.

Biology of two important diseases

Although the treatments and pest control strategies used in the experiments described here were not intended to have an impact on diseases, it was deemed important to evaluate their effect on the progress of two of the most important fungi in strawberry production; grey mould (*Botrytis cinerea*) and powdery mildew (*Sphaerotheca macularis* f. sp. *fragariae*).

Grey mould

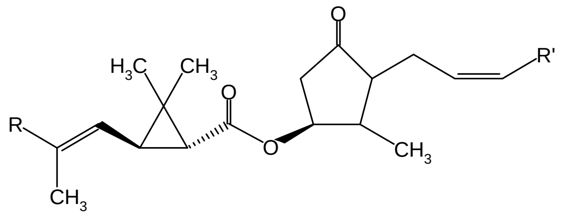
The most obvious symptoms of grey mould are mummified fruits covered with grey dusty powder. The infection starts in senescing flowers and then enters the green fruit. When the fruit matures, the fungi may become active. Disease development is favoured by warm temperatures and wet conditions (Wilcox & Seem, 1994). Dead leaves have been found to be the most important inoculum source (Braun & Sutton, 1987).

Powdery mildew

Early symptoms of powdery mildew in strawberry plants are curling leaf edges and purple-brown patches on the leaves. Later, powdery mycelium develops on the undersides of leaves. Serious damage to the foliage caused by dense mycelium coverage results in a reduction in photosynthesis. Infected fruits fail to ripen and may also be covered by powdery mycelium. The pathogen overwinters in infected leaves and dispersal of conidia is windborne (Hancock, 1999a). Conidial germination is facilitated between 15 and 25 ºC and with 75 and 98% relative humidity (Amsalem *et al.*, 2006).

Control methods investigated

Although conventional pesticides are not allowed in organic production, there are other options available. For organic farming the selection and breeding of cultivars resistant to pests and diseases are of vital importance. The use of beneficiary organisms for biological control of pests is becoming increasingly common. Also of importance, are plant extracts that function as repellents or insecticides. Crops



	R	R'
A:	$-CH_3$	$-CH=CH_2$
B:	$-COOCH_3$	$-CH=CH_2$
C:	$-CH_3$	$-CH_3$
D:	$-COOCH_3$	$-CH_3$
E:	$-CH_3$	$-CH_2CH_3$
F:	$-COOCH_3$	$-CH_2CH_3$

Figure 5. Chemical structure of natural pyrethrins; Pyrethrin I (A), Pyrethrin II (B), Cinerin I (C), Cinerin II (D), Jasmolin I (E) and Jasmolin II (F).

can also be protected from pests by physical barriers preventing the damaging organisms from entering the field. In this experiment two cultivars, 'Honeoye' and 'Cavendish' with a low susceptibility to grey mould were chosen as a preventive measure and three options of direct control were evaluated; a plant extract (botanical control), a physical barrier (physical control) and a predatory mite (biological control). Interactions between the treatments were also studied.

… a botanical control agent

In conventional production of strawberries the synthetic form of pyrethrins (pyrethroids) is used before flowering and after harvest to control the strawberry blossom weevil. In organic production it is permissible to use the botanical insecticide pyrethrum. This is an extract from the flowers of *Tanacetum cinerariaefolium*, which belongs to the *Chrysanthemum* plant genera. The extract contains natural pyrethrins, which are lethal or knockdown the insect (Katsuda, 1999) (Figure 5). Experiences from an earlier experiment using the cultivars 'Kent' and 'Bounty' showed that spraying with pyrethrum resulted in less damage by the strawberry blossom weevil on flower buds (Svensson, 2002).

Due to the rapid breakdown of pyrethrins by air and sunlight, they are considered to have a low impact on the environment (Angioni *et al.*, 2005; Antonious, 2004). To increase the stability of the active ingredients, synergists like piperonyl butoxide are often added to the extract. However, addition of piperonyl butoxide was not allowed by the only authorised inspectorate of organic production (KRAV) in Sweden at the time of the field work and thus no synergist was added to the pyrethrum used in the experiment.

…a physical control agent

The most common reason for using polypropylene fleece (Agryl) in production of strawberries in our climate is to protect the plants from frost injury or to produce a 'forced' crop, *i.e.* covering the plants in spring to bring forward the harvest. However, the fleece could also be used as a physical barrier to prevent strawberry blossom weevils from migrating into the field from hibernation sites outside. There is an obvious risk that beneficial insects such as pollinators *etc.* could also be excluded and this must be considered. Another negative effect is the increased

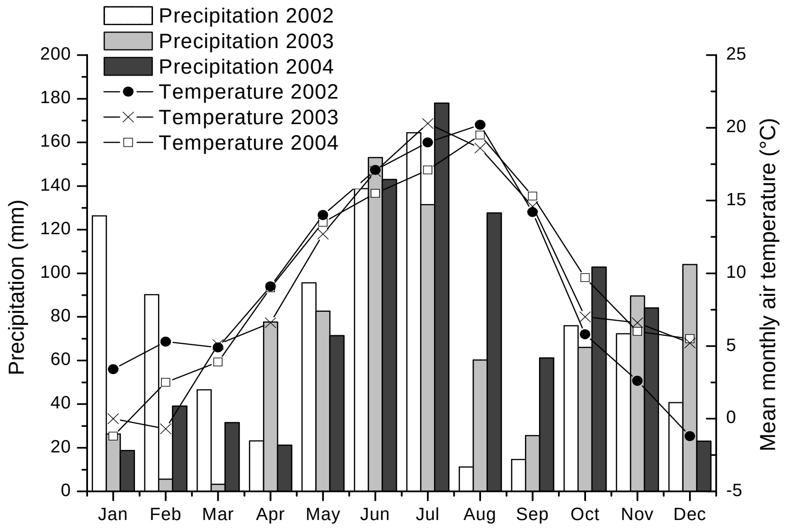


Figure 6. Monthly accumulated precipitation and mean air temperature during the experimental period 2002-2004 at Rånna Experimental Station, Skövde.

risk of infection by grey mould and other organisms with the altered microclimate under the fleece cover (Wilcox & Seem, 1994).

… a biological control agent

The strawberry mite's position in the plant keeps it well protected from acaricides in conventional production. In organic production the use of predatory mites may be an option to control the strawberry mite. *Neoseiulus (Amblyseius) cucumeris* (Oudemans) (Acari: Phytoseiidae) is a well-known, commercially available, predatory mite that can attack strawberry mites (Easterbrook, Fitzgerald & Solomon, 2001). In Sweden, this predator does not overwinter successfully in the field and there is an immediate risk of frost killing the organism on early release in the spring. However, early release is desirable to avoid a large build-up of the population of strawberry mites and repeated releases may compensate for losses in early releases due to frost.

Methodological aspects

The thesis was based on data from field experiments conducted at Rånna Experimental Station, located outside Skövde in Sweden (58°27'N, 13°51'E). The soil at the site is a sandy moraine loam with 6.0% clay and 2.2% organic matter. Precipitation and air temperature at the site (Figure 6) were recorded using a weather station (METOS® - D, version 1.0/92).

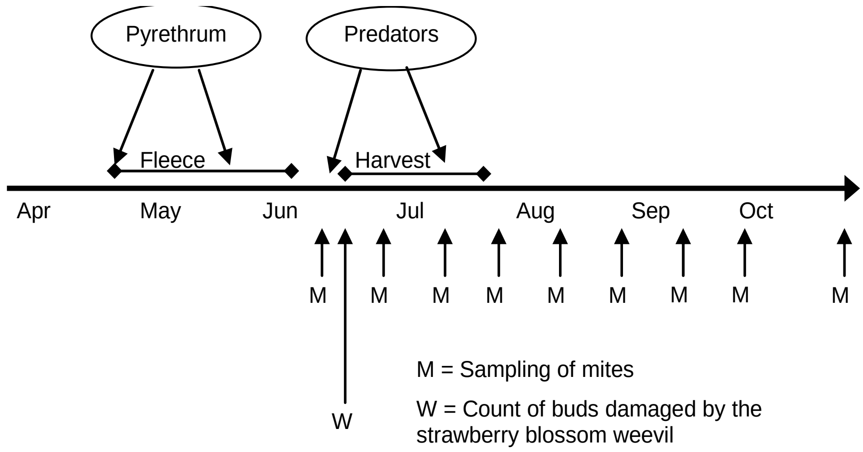


Figure 7. Overview of the different treatments and sampling occasions in the **pest control strategy** experiment (Paper III).

The experimental plots were planted in single rows to create an open crop, minimising high humidity and thereby also decreasing the risk of infection by grey mould. The strawberry plants were irrigated with overhead sprinklers and covered with straw during the winter to protect them from winter frosts. Straw was also used during summer to keep the berries clean. The early ripening cultivar Honeoye was chosen for its high yield capacity and suitability in organic production, due to its high resistance to grey mould (Papers I-III) (Daugaard & Lindhard, 2000; Rhainds, Kovach & English-Loeb, 2002). A second cultivar, 'Cavendish', had shown promising results in earlier experiments at the experimental station and was therefore added to the pest control strategy experiment (Paper III). A third cultivar, 'Korona', was used in the dispersal pilot study because strawberry mites are known to establish well on this cultivar according to advisors and growers in the area (Paper IV).

In two of the experiments the focus was on fertilisation with organic fertilisers and use of photodegradable plastic mulch (Papers I-II). In the first experiment (Paper I), the impact on **plant establishment** of fresh or dried poultry manure in combination with or without degradable plastic mulch was evaluated. In the second experiment (Paper II), the main emphasis was on nutrient supply during the **cropping period**, and three different fertilisers and one unfertilised control were combined with or without the degradable plastic mulch. The fertilisers used were urine from cattle, vinasse (a by-product from yeast production) and dried poultry manure. These were chosen since they had been used in previous experiments at the research station and shown promising results (unpublished data) and are easily available to growers. The fertilisers were applied in spring and after harvest. In these two experiments the number of crowns, runners and healthy plants were counted and the dry weight of the plants was recorded. The fruit yield was measured and divided into four different classes at harvest; marketable yield, and fruit damaged by grey mould, powdery mildew and other damage respectively. In addition to this, unripe green fruit were stored under moist conditions to investigate the proportion of fruit with latent infection of grey mould (Paper II). The amount of mineralised nitrogen in the soil was also recorded from soil samples taken with an auger as close to the plants as possible (approximately 10-15 cm away). In the second experiment, plots without plants were established to enable the amount of mineralised nitrogen in the soil to be measured without disturbance from plant uptake. The soil samples were taken from the 0-15 cm (Papers I-II), 15-30 cm (Paper I) and 30-60 cm (Paper I) soil layers. Strawberry plants have a shallow root system and the majority of the soil samples were taken at 0-15 cm to analyse the amount of nitrogen available in the root zone.

In the third experiment the focus was on two important pests (Paper III). The aim was to find a **pest control strategy** to minimise the damage caused by both strawberry mites and strawberry blossom weevils, and to identify possible interactions between the treatments used. Fleece was used to prevent the weevils from entering the plots from external overwintering sites and pyrethrum was sprayed as a control agent. To avoid negative effects from exclusion of pollinating insects, the fleece was removed when approximately 50% of the flowers were open (Figure 7). To control strawberry mites, the predatory mite *Neoseiulus cucumeris* was released in the same experiment. The number of buds damaged by the strawberry blossom weevil was counted just before the first harvest, and strawberry mites were counted on furled leaves using a stereomicroscope (Figure 7). The fruit yield was recorded and divided into the same classes as for the plant nutrition experiments, and the fruit were also checked for latent infection by grey mould.

The fourth experiment was a pilot study where the aim was to learn more about the innate **dispersal** capacity of strawberry mites within a field (Paper IV). The

Table 2. *An overview of the experimental setups in the different papers (I-IV) included in this thesis. All four experiments were located at different sites at Rånna Experimental Station.*

	Plant establishment (Paper I)	Cropping period (Paper II)	Pest control strategies (Paper III)	Dispersal (Paper IV)
Design	Randomised block	Randomised block	Split-plot	--
Block (no.)	4	3	4	4
Plots / block (no.)	4	8	2 main plots 6 subplot/main plot	25
Plants / plot (no.)	30	35, 32, 29 (destructive sampling)	30 plants/subplot	4
Plantation (year)	2001	2001	2001	2002
Sampling (year)	2002	2002-2004	2003-2004	2003-2004

experimental site was pre-checked to make sure that no strawberry mites were already in the field before the controlled release. Strawberry mites from a field e nearby were applied in the middle of each block, which consisted of 5 rows, and the number of mites on one furled leaf from each plant was counted using a stereomicroscope after 2 months and after 12 months. Only personnel with clean clothes and boots were allowed to enter the field.

The experimental set-ups used were a randomised block design (**plant establishment**, Paper I; **cropping period**, Paper II) and a split-plot design (**pest control strategy**, Paper III) (Table 2). The split-plot design was chosen in order to allow the appropriate amount of predatory mites to be released and to allow the predatory mites to disperse along and between the rows regardless of borders between subplots (Figure 8). The pilot study concerning strawberry mite **dispersal** (Paper IV) was statistically analysed by comparing movements within and between plant rows (Table 2).

Results and discussion

Fertilisation strategies and mulching

Plant establishment (Paper I)

Strawberry plant establishment measured in terms of yield, number of runners and healthy plants was improved by the use of degradable plastic mulch (Table 3; compilation of the results). The increase in yield of 60% with the use of plastic mulch compared with no mulch might be explained by more flowers being initiated in the autumn due to higher amounts of nitrogen in soil in October (Figure 9). The increased number of runners per plant (0.9 compared with 0.1) in the first autumn

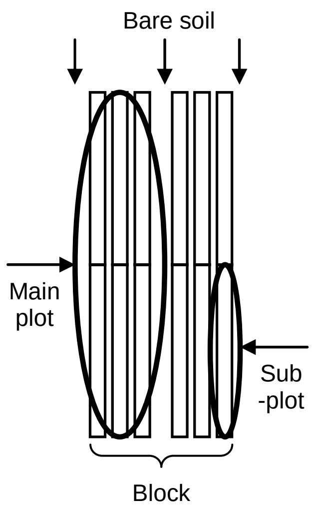
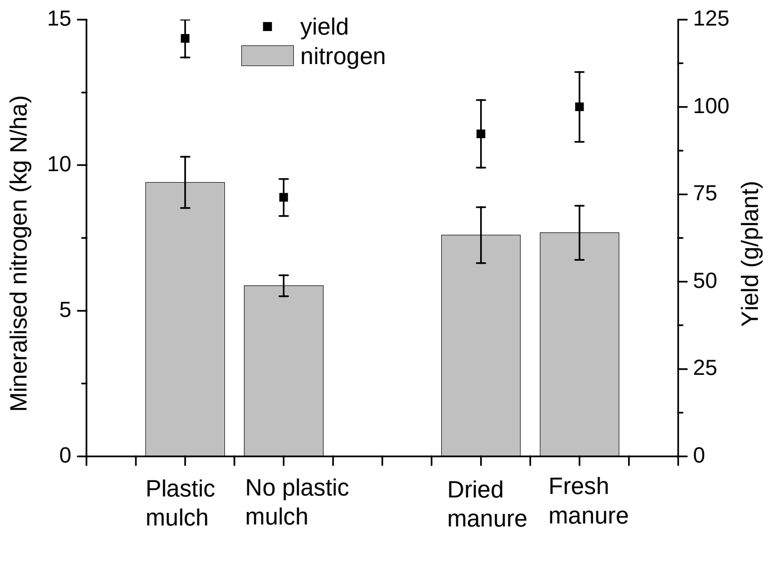


Figure 8. Diagram of a block in the split-plot experiment (Paper III). Predatory mites were released in one of the main plots in each block. In the subplots, the six combinations of cultivar (2) x treatment against strawberry blossom weevil (3) were randomised.

after plantation also indicates that the plants had a more favourable growing situation during this period. There was a higher amount of mineralised nitrogen in all three soil layers investigated under the plastic mulch in the first autumn after plantation. The differences between the mulch treatments in the 30-60 cm soil layer might be due to increased mineralisation earlier in the season in soils with plastic mulch than in plots with no mulch. An alternative explanation is that the higher quantity of N under the plastic mulch was due to decreased nitrogen leaching to lower layers compared with bare soil.

The results also showed that the degradable mulch affected harvesting time, as the differences in yield occurred mainly during the beginning of the harvest. It is well known that black plastic mulch makes strawberries ripen earlier in the season (Plekhanova & Petrova, 2002), which also seems to be the case with degradable plastic mulch. There were also more healthy plants with plastic mulch in the first year although the differences were small (29.5 with plastic compared with 28.4 without plastic, $p<0.05$). In the second year there were no such differences.

There were no differences in yield, plant growth or amount of mineralised nitrogen in the soil in the autumn resulting from type of manure used that could compensate for the higher cost compared with using fresh poultry manure. Furthermore, there were no interactions between the mulch and the fertilisers used and none of the treatments affected the incidence of fungi.



Figur 9. Amount of mineralised nitrogen in the 0-15 cm soil layer in October 2001 and accumulated yield in 2002. The strawberries were planted in August 2001.

Cropping period (Paper II)

This experiment showed that the use of degradable plastic mulch had a stronger impact on yield than extra addition of fertilisers (Table 3; compilation of the results). Here too, there were no interactions between the plastic mulch and fertilisers used. In the first two years of harvesting, the use of plastic mulch increased the marketable yield by 80% and 27% respectively compared with treatments with no mulch. The yield increase was most likely explained by more fruit being initiated, since there were no significant differences in discarded fruit and fruit size between the treatments. An increased number of fruit might be a result of an increase in temperature and better water conditions under the mulch, resulting in a faster plant establishment as indicated above. A previous study with photodegradable plastic in a blackcurrant crop showed an increase in soil temperature (1.9 ºC) and higher soil moisture in spring and summer compared with no plastic mulch (Larsson & Båth, 1996). Although not statistically significant, there was a tendency ($p=0.063$) for higher dry weight of plants with plastic mulch in the first year and this might support the theory of more favourable conditions during plant establishment. Higher marketable yield with plastic mulch was also reported by Birkeland, Døving & Sønsteby (2002). In contrast to their conclusions, however, the number of fruit infested with grey mould was not higher in plots with degradable plastic mulch in the present experiment. Higher yields and vegetative growth with black plastic mulch have also been reported by Haynes (1987). Although the higher temperature generated and better water conditions under the mulch are known to increase N mineralisation (Neuweiler, 1997), we found no effect of the mulch on mineralisation, in contrast to the results in Paper I.

In the third year of cultivation there were no significant differences between the treatments with plastic mulch and without, and this was probably due to insufficient plant renewal in plots with plastic mulch. Since the plastic mulch was photodegradable it was supposed to break down to allow runners to establish between the plants, but the straw used to keep the strawberries clean and protected from frost probably slowed down this photodegradation.

As previously mentioned, none of the fertiliser treatments in this experiment increased the yield. One explanation for this might be that the amount of starter fertiliser supplied was optimal. However, this is contradicted by mineralised N analyses, which showed very low amounts in control plots both with and without plants. Before the experimental field was used in this study, it was harrowed repeatedly for four years to minimise the amount of rooted weeds. During this period no fertilisers were applied and the organic pool and microbial activity was most likely very low at the beginning of the experiment. This theory is to some extent supported by a pot experiment by Langmeier *et al.* (2002), who showed that a greater proportion of N applied as cattle manure was taken up by plants grown in organically managed soil than in conventionally managed soil. Their hypothesis was that the organically managed soil had a higher microbial activity. This was also supported by Peacock *et al.* (2001), who suggested that soil practices that provide slowly mineralisable nutrients and enhance soil carbon may result in a larger microbial community. However, this conclusion was partly rejected by

Shannon, Sen & Johnson (2002), who found that the differences in microbial communities between organically and conventionally managed soils were ‘subtle rather than dramatic’. Pang & Letey (2000) found in multi-year simulations that it took two or more years to reach maximum yield because of unmineralised manure and accumulation of mineralised N after crop uptake. They suggested that high applications to build up the organic pool followed by reduced inputs in subsequent years would be appropriate after conversion from conventional to organic production.

There are also several studies that show the importance of timing of fertilisation (Archbold & MacKown, 1995; Strik, Righetti & Buller, 2004). One study showed a shift in partitioning pattern of nitrogen within a relatively short timeframe. Nitrogen applied at anthesis partitioned at higher levels to crowns and roots, while when applied at first fruit ripening it partitioned to generative organs (Nestby & Tagliavini, 2005). In the present experiment the marketable yield was negatively affected by vinasse (2003) and vinasse and urine (2004). The result from 2003 can be explained by significantly (p=0.034) higher infestation of powdery mildew in vinasse-treated plants (24.2% of total yield) compared with the control (11.8% of total yield). In 2004 the dry weight of vinasse and urine-treated plants was 35-50% higher than that of the control but the differences were not significant (p=0.096). These fertilisers were applied three to four weeks after the poultry manure because they were expected to mineralise more rapidly. This may have caused a shift in distribution of nitrogen to vegetative growth. The final conclusion is that the lack of effect of fertiliser on yield might be the result of a combination of low microbial activity and a failure to time the application correctly in relation to crop development.

Pest control strategies (Papers III-IV)

Strawberry blossom weevils

The double treatment with pyrethrum before 50% of flowers were open did not decrease the number of buds damaged by the strawberry blossom weevil in any of the cultivars (Figure 10) (Table 3; compilation of the results). This is in disagreement with Labanowska (2002), who achieved satisfactory control of the weevil in the strawberry cultivar Senga Sengana. In her experiment the plants were treated once just before flowering. However, in our experiment, in which pyrethrum was combined with a fleece cover, the number of damaged buds decreased in one of the two cultivars examined. In ‘Honeoye’ the number of buds damaged by weevils was reduced from 39% to 17% in 2003 and from 21% to 10% in 2004. In ‘Cavendish’ there was no such significant reduction (Figure 10). These differences may be explained by different flowering periods in relation to the development of the insect pest, since ‘Honeoye’ flowers approximately one week earlier than ‘Cavendish’. The even earlier flowerings in ‘Honeoye’ under the fleece cover, due to higher temperature, may have preceded the oviposition of *A. rubi* and thereby decreased the number of buds available when the weevil was ready to oviposit. However, there are reports that susceptibility to *A. rubi* is also under genetic control (Simpson, Easterbrook & Bell, 2002).

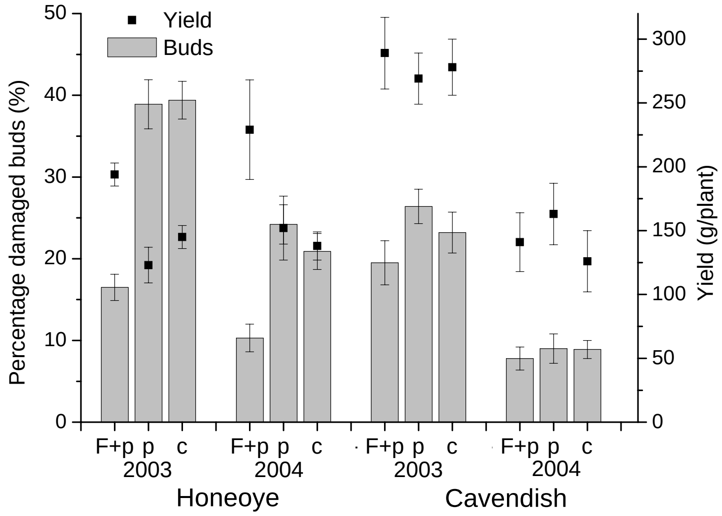


Figure 10. Percentage of buds damaged by weevils and yield in 'Honeoye' and 'Cavendish' during 2003 and 2004 (mean values ± SEM). F+p = fleece + pyrethrum, p = pyrethrum, and c = untreated control

The decrease in damaged buds in 'Honeoye' was followed by a significant increase in yield (Figure 10). There are well-known plant growth enhancing effects of fleece covering during early spring that also might explain the increased yield. Bushway & Pritts (2002) showed that fleece covering increased starch accumulation in the leaves, and increased photosynthetic rates of overwintering and spring leaves. They also found an increase in yield and this was explained by an increase in the number of marketable secondary and tertiary fruit. An increase in yield due to development of tertiary berries after fleece covering was also shown by Gast & Pollard (1991b). Those authors also showed earlier photosynthesis after the winter period in covered plants compared with uncovered (Gast & Pollard, 1991a). However, our experiment showed no increase in yield in 'Cavendish' after fleece covering.

There are strawberry cultivars that compensate for damaged buds. In simulation studies, both 'Kent' (English-Loeb *et al.*, 1999) and 'Elsanta' (Cross & Burgess, 1998) could tolerate bud damage or flower removal without a significant reduction in yield. However, the decrease in yield in 'Honeoye', in the present experiment is in agreement with Faby *et al.* (2004).

The effect of pyrethrum in the combined fleece and pyrethrum treatment was unclear. However, when only pyrethrum was used it did not affect the number of damaged buds, which indicates that most of the positive effect of the combined

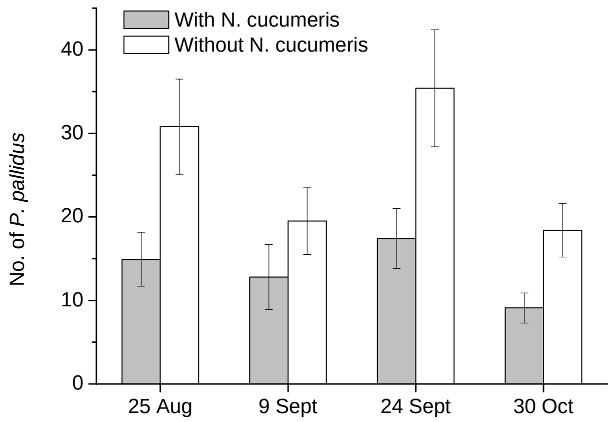


Figure 11. Number of strawberry mites in 'Cavendish' during the period with the largest population build-up in 2003 (mean values ± SEM).

treatment against *A. rubi* was probably due to the fleece used as a physical barrier to prevent the strawberry blossom weevils from migrating into the field.

Strawberry mites

There were large differences between the two cultivars in terms of numbers of *P. pallidus* (Table 3; compilation of the results). In 'Cavendish' the number ranged from 3 to 26 and in 'Honeoye' from 1 to 5. Despite these differences, both cultivars showed clear symptoms of mite infestation, especially in 2004. Due to the low infestation level in 'Honeoye', only results from 'Cavendish' could be analysed.

The release of *N. cucumeris* reduced the population of strawberry mites significantly at the end of the season (Figure 11). This is in agreement with Easterbrook, Fitzgerald & Solomon (2001), who showed a 70% reduction in strawberry mites after release of *N. cucumeris* under greenhouse conditions. They also emphasise the importance of establishment of the predatory mite before the population of strawberry mite becomes too large. Although as many as 40 *N. cucumeris* per plant were released twice a year in our experiment, almost no predatory mites were found in the leaf samples and no predator:prey ratio could be calculated. The initial predator:prey at the first release was approximately 10:1.

When strawberries are grown as a perennial crop, it is important to reduce the population build-up to avoid large populations of strawberry mites in the following year. In this experiment, the number of *P. pallidus* increased tenfold within one year in plots without the predatory mite. It is also important to keep the numbers low to avoid negative effects on flower initiation in the post-harvest period. Stenseth & Nordby (1976) calculated a yield reduction in 'Senga Sengana' based on the number of strawberry mites in the post-harvest period of the previous year and found that more than 35 mites per leaflet reduced fruit yield by 23%. In our experiment the number was below their estimated level for yield reduction and even though the numbers of strawberry mites were significantly reduced by the release of predatory mites, there was no increase in yield.

Interactions and effects on non-targets

Although the fleece cover was applied to minimise the number of buds damaged by the strawberry blossom weevil, it also affected the number of strawberry mites. The combined treatment with fleece and pyrethrum increased the overall mean number of strawberry mites for the whole season from 6 mites/leaf to 15 mites/leaf in main plots with *N. cucumeris*, and from 18 mites/leaf to 26 mites/leaf in main plots without, but these increases were not statistically significant (p=0.057 and 0.096 respectively) (Figure 12). Easterbrook *et al.* (2003) showed that the development time of strawberry mites decreased from 28.4 days at 12.5 ºC to 8.8 days at 25 ºC, with oviposition rate increasing accordingly. Although the findings in our experiments were not significantly different, the larger populations may have been caused by a higher temperature under the fleece cover.

We had expected an increased amount of fungi under the fleece cover (Wilcox & Seem, 1994). However, the number of fruits infested with grey mould was very low during the experimental period and no negative effect of the combined fleece and pyrethrum treatment could be detected.

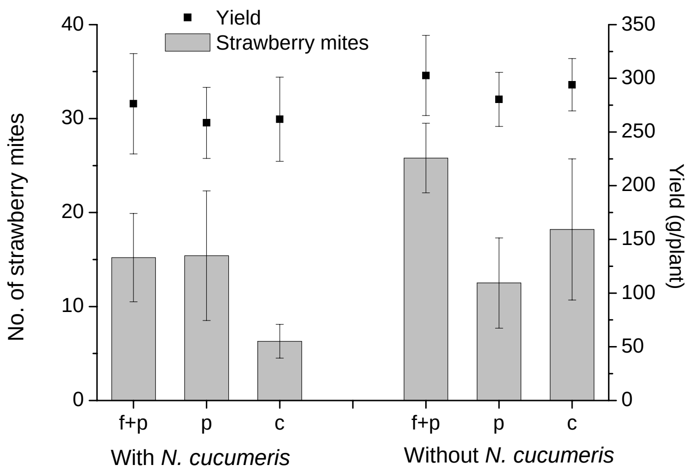


Figure 12. The interaction between the treatments against strawberry blossom weevil and strawberry mites. Mean seasonal number of strawberry mites and yield in 'Cavendish' 2003 (mean ± SEM).

Mite dispersal

In the pilot study (Paper IV), after 2 months the mites had already reached the boundary of block 4. This indicates that the plot size was not large enough to draw any sound conclusions concerning mite migration. Furthermore the dispersion in this block was faster than anticipated Indicating that the temporal resolution was not sufficient. The statistical analysis indicated that the mites moved more easily within the plant rows than between them.

Practical implications

Choice of cultivars

Both 'Honeoye' and 'Cavendish' performed well in terms of their resistance to fungi and their relatively high yield. In general, choice of cultivar is greatly dependent on location, local climate and abundance of pests. Cultivar choice is one of the most important single factors for organic strawberry production, as choosing the wrong cultivar inevitably leads to problems.

Control of mites

The grower must always have a preventive approach concerning mites. Since the mites have a relatively slow dispersion, starting off with clean and healthy plant material is essential for production. Daily maintenance should be carried out in newly established fields to prevent the spread of pest from older fields.

Mulching and predatory mites

Plastic mulching results in rapid establishment of strawberry plants and a higher yield during the two first years of the crop. The mulching also helps to control weeds, which always create a high demand for labour in organic farming. Although perhaps not acceptable within true organic farming, the use of plastic mulching in production is recommended. A more environmentally friendly alternative is to use plastics based on *e.g*. maize starch. The combination of plastics and straw gives a good environment for the predatory mites and also decreases the rate of degradation of the plastic.

Fleece covering

Fleece is used both for winter protection and for prolonging the season in spring and autumn. In organic production, fleece also has a pest control function. Although 'Honeoye' was attacked by strawberry blossom weevils, the use of fleece covering had a positive effect since it limited the damage done to the cultivar. However, with 'Cavendish' the fleece had a negative effect, since it promoted strawberry mite infestation in the crop. This might have been avoided by the use of entirely clean plants at establishment of the crop. Fleece covering is recommended if the plant health aspects are taken into consideration.

Fertilisation strategy

The experiments indicate that only the initial starter fertilisation is needed, as further booster applications of fertiliser showed no positive impact. Based on these results, it might not be necessary to apply further doses of fertiliser during the cropping period.

The use of pyrethrum

Pyrethrum has a wide effect on a number of insects and mites, both pests and beneficial organisms. However, in the present study this agent had no effect on strawberry blossom weevil and therefore its use in organic production for this purpose cannot be recommended.

Table 3. *Compilation of the results in Papers I-III. All treatments except cultivar and primary fertilisation are compared with untreated controls*

Treatments		Marketable yield	Amount of mineralised N in the soil	Plant growth	Fruit size	No. of damaged buds by strawberry weevils	No. of strawberry mites	Fungal infection (in the field)	Paper
Cultivar	'Cavendish'	+ (2003) 0 (2004)	n.a.	+ (b, 2003) 0 (b, 2004)	0	+ (2003) - (2004)	+	+ (gm, 2003) - (pm, (fleece) 2003) 0 (2004)	III
	'Honeoye'	- (2003) 0 (2004)	n.a.	- (b, 2003) 0 (b, 2004)	0	- (2003) + (2004)	-	- (gm, 2003) + (pm, (fleece) 2003) 0 (2004)	III
Ground cover	Degradable Plastic mulch	Paper I: + Paper II: + (year 1-2) 0 (year 3)	Paper I: + (October) 0 (April) Paper II: -	Paper I: + (r) 0 (cr, dw) Paper II: 0 (cr, year 1-2; r, year 1; dw) + (cr, year 3; r, year 2-3)	Paper I: n.a. Paper II: 0	n.a.	n.a.	Paper I: 0 Paper II: - (pm, year 2) 0 (pm, year 1 & 3; gm)	I-II
Starter fertilisation	Fresh poultry manure	0	- (April) 0 (October)	0	n.a.	n.a.	n.a.	0	I
	Dried poultry manure	0	+ (April) 0 (October)	0	n.a.	n.a.	n.a.	0	I
Fertilisation during crop-ping period	Urine	0 (year 1-2) - (year 3)	+	+ (r, year 1) 0 (r, year 2-3) 0 (cr, dw)	0	n.a.	n.a.	0 (pm; gm)	II
	Vinasse	0 (year 1) - (year 2-3)	+	0 (cr, r, dw)	0	n.a.	n.a.	+ (pm, year 2) 0 (pm, year 1 & 3; gm)	II
	Dried poultry manure	0	+	0 (cr, r, dw)	0	n.a.	n.a.	0 (pm; gm)	II
Pest control	Pyrethrum	0	n.a.	n.a.	0	0	+ (Nc, p=0.051) 0 (no Nc)	0	III
	Pyrethrum + fleece	+ 'Honeoye' 0 'Cavendish'	n.a.	n.a.	-	- 'Honeoye' 0 'Cavendish'	+ (Nc, p=0.057) 0 (no Nc)	0	III
	Predatory mites	0	n.a.	n.a.	n.a.	n.a.	-	n.a.	III

+ = increase; - = decrease; 0 = no effect; n.a. = not analysed; b=buds; c=crowns; r=runners; dw=dry weight; pm=powdery mildew; gm=grey mould; Nc=*N. cucumeris*

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Äntligen har stunden kommit då det är dags att säga tack till alla som har varit inblandade i det här projektet på ett eller annat sätt. Jag hoppas verkligen att jag har haft hyfs nog att visa min uppskattning under projektets gång, så att ni vet hur tacksam jag är. För att undvika risken att glömma någon vill jag bara säga:

TACK...

…alla kära vänner och trevliga kollegor!

Det är ändå några personer som jag vill nämna speciellt och då börjar jag med familjen Einarsson; - Kicki, Gugge, Mikael, att få jobba med er på Rånna försöksstation har varit en fröjd. Ert vänliga bemötande och kunnande gjorde min tid på stationen till något speciellt.

Jag har ju haft förmånen att flera handledare som alla har bidragit på sitt vis. Ett stort tack till: Birgitta Svensson (du har varit en fast punkt och en räddande ängel upprepade gånger), Christer Nilsson (alltid intressant att diskutera insekter med dig), Ulla Gertsson (för konstruktiv input om växtnäring), Birgitta Rämert (du kom in som en katalysator på slutet) och Rolf Larsen (du släpade mig över mållinjen när motivationen nästan var slut).

Sara Bergquist (stavade jag rätt?) och Lars Mogren! Kära f.d. doktorandkollegor, det vi inte har diskuterat om doktoranders vedermödor på våra pepp-möten är inte värt att nämnas.

Slutligen vill jag tacka min lilla familj, Mattias, Elsa och ”lillasyster”. Jag älskar er!

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