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Development of sustainable plant protection programs through multi-actor Co-innovation: An 8-year case study in Swedish apple production

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ABSTRACT

This article assesses the multi-actor co-innovation research that was carried out between 2010 and 2018 by researchers and apple production actors. The aim was to develop sustainable integrated pest management methods that, with the help of an agroecological whole system approach, would be both desirable and feasible to implement in practice. Whilst a novel pest management strategy based on semiochemicals arrived at and was rapidly adopted by growers, the enhancement of biological control through functional diversity required long-term learning. This is explained by substantial differences in the perception of the economic risk and the necessary knowledge behind the adoption of each method. The knowledge gap due to the reduced number of extension advisors and the conflict between the cost incurred when implementing low-impact pest control methods and reduced profitability of apple crops were pointed out as major contradictions by the actors. We suggest that strengthened regional agro-ecological infrastructure support along with the expansion of public advisory service personnel would reduce the farmer economic risk and share the responsibility for a safer environment and healthier food. Similarly, relevant authorities should be provided with resources to allow for safety assessments of candidate low-risk plant protection products at the regional scale. As a conclusion, we recognised that in our region sustainable agroecosystem management through feasible and desirable plant protection strategies could not be developed solely by focussing on the efficiency of the tools because the cost-effectiveness and thus the implementation of such tools depended greatly on the simultaneous co-innovation of the socio-technical system. Local stakeholders need to harmonise their vision and standpoints to engender long term socially and environmentally sound objectives providing a base to promote, finance and extensively adopt innovative plant protection strategies within the Skåne region.

1. Introduction

Food production is facing a number of challenges arising from global changes to the environment and society (Ripple et al., 2017). Awareness upon environmental degradation and the health hazards caused by agricultural intensification over the last six decades necessitates new food production systems (Tittonell, 2014). The European Union (EU) Directive 2009/128/EC and Regulation 1107/2009/EC supports the implementation of sustainable standards such as Integrated Pest Management (IPM). IPM is an ecosystem-based interdisciplinary strategy, which emphasises pest management measures with the least negative effect upon human health, non-target organisms and the environment whilst still providing satisfactory control.

The EU requires that all member states base their National Action Plans on eight IPM principles to be followed by all professional pesticide users (Barzman et al., 2015). The principles are often visualised in a pyramid where the preferred methods are emphasised by being placed at the base of the triangle occupying the largest area. Preventive measures are prioritised and can be

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considered as the creation of cropping systems less likely to experience significant economic losses due to the presence of pests. When measures such as landscape and habitat management, host plant resistance and cultural practices fail, direct control interventions are used. Direct control measures also vary in the level of negative side effects depending on their mode of action, persistence, toxicity and timing. Finally, control measures can increase in efficiency and decrease their non-target effects with the help of resistance management, monitoring (emphasis on pests and diseases), forecasting models and threshold values. The final principle states the need to learn about the effect of the selected and documented control methods by evaluating the results.

From the origins of IPM, the idea of combining biological and chemical control was proposed to overcome the emergence of resistance as well as to preserve beneficial arthropods in walnuts (Michelbacher and Bacon, 1952). Subsequently, concepts such as economic threshold and injury level were added (Stern et al., 1959). Due to the growing evidence of the negative side-effect of broad-spectrum pesticides, the IPM concept moved towards a more holistic perspective, the so-called Integrated Production (IP), which included the sustainability of the entire farm (Pechin and Dhawan, 2009) and was promoted by the International Organisation for Biological Control (IOBC, 2018a). Additional work is nonetheless necessary to shift from a reactive to a proactive pest management. To do this, a redesign of cropping system is a current necessity, although it is often left unaddressed by most IPM research programs (Simon et al., 2010).

Pome fruit production is regarded as a pioneer sector for IPM in Europe (Freier and Boller, 2009). Pome fruit IPM has been implemented over the last 30 years and the sector has largely contributed to worldwide IPM development (Damos et al., 2015). Despite scientific and political efforts to advance towards the implementation of varied innovative pest control methods (with an emphasis on preventative ones), the reality of IPM is far from ideal (Hokkanen, 2015) and there remains a disparity between the theoretical IPM concept and its application in reality (IOBC, 2018b). Until today, a lack of opportunities to foster interdisciplinary approaches of pest control is recognised. The innovative design of orchards to minimise reliance on pesticide is a current challenge. Some authors suggested new visions for the design of diversified agroecological cropping systems (i.e. relying on ecology-based processes rather than external inputs) (Simon et al., 2011). However, such an approach requires new knowledge. There is a need to gather skills, experiences and insight from researchers and other stakeholders (e.g. growers, advisors) in different European fruit districts and contexts to account for the complexity of agro-ecosystems such as orchards and consider within-space and −time interactions (Simon et al., 2010, 2011).

The practical implementation of IPM involves iterative interaction between laboratory research, field experiments, and multiple stakeholders to foster co-learning and innovation. The gaps in this process were often recognised as a limitation for the development of IPM strategies by Swedish stakeholders. A strong effort is required to design new strategies bridging the gap between theoretical and applied ecology, along with a multi-actor innovation systems (Vänninen et al., 2015).

The work of the Integrated Plant Protection (IPP) research unit at the Swedish University of Agricultural Science is in line with this school of thought. In order to increase the relevance and implementation of its IPM research in practice, the research unit engaged in multi-actor co-innovation through a series of research projects in different crops that were carried out during 2010–2018. Main collaborating actors were growers, their advisors and the Swedish Board of Agriculture (Jordbruksverket). Through the analysis of two case studies with relation to Swedish apple production, we answered the following research question: to which extent the collaboration between stakeholders achieved the aim to develop IPM strategies that would be desirable and feasible to implement? Encountered problems and possible solutions, including from a wider socio-economic perspective, are discussed.

2. Methodology

2.1. Participatory methodology: establishing shared goals via stakeholder participation

All research projects were to different extent based on identified needs through stakeholder participation (Table 1). Several projects also applied a varying degree of participatory methodology during the project management, analysis, conclusion and communication of results. This part of the process will be described under each case study and in Tables 1 and 2. The participatory action research (PAR) approach adopted follows the pragmatic paradigm described by Mertens (2015), which allows for the use of mixed methods depending on the needs of the situation and the research question. All quantitative (field and laboratory experiments) and qualitative (workshops, interviews, group meetings) methods were situated within a broader qualitative framework where problem formulation, innovative design of strategies and systems, data collection and evaluations were performed collaboratively across projects.

Within the given national background, we organised five annual full day apple workshops “Äppelträffen” with approximately 50–60 participants (Table S1) each between the years 2010 and 2015. Researchers within different fields of apple research and advisors were invited to present and discuss their work together with apple growers, Swedish Board of Agriculture officials and pest management companies. During the second session of each Äppelträff the participants were divided into working groups according to themes suggested by them. Each group was appointed a facilitator and secretary which had received previous training. Each participant presented their problem formulation, possible research and development actions were discussed and an action plan involving the next step and relevant stakeholders was suggested and presented to the remaining groups at the end of the workshop. In these meetings growers and advisors identified tortricids, aphids and the apple sawfly as the most difficult pests to manage. Growers were also concerned about the increase in scale pest population possibly due to a decrease of natural enemies in orchards caused by a change of pesticides. Knowledge gaps were considered within these subjects, and research questions were formulated accordingly. Based on these prerequisites, we assembled participatory research proposals to request financial support from national and European funding agencies (Table 1).

Projects that were financed included (1) “Web-based monitoring of tortricids - a pilot project on integrated pest management”, (2) “Development of pest management strategies in organic apple production in collaboration with farmers utilising complementary biological control strategies”, (3) “Development of an integrated pest management strategy for the control of insect pests of apple orchards in collaboration with growers, advisors, pheromone producers and researchers”, (4) “Study of the control exerted by natural enemies over aphids and scales in apple orchards and the management factors affecting the natural regulation of pests they provide”, (5) “Enhancement of pest management resiliency in apple orchards through a synergy between semiochemicals and conservation biological control”, (6) “Eco-orchard: Innovative design and management to boost functional biodiversity of organic orchards” and (7) “Eco-Fruit: Managing ecosystem services for fruit production in different European climates”. Projects were supported by the Swedish Farmers’ Foundation for Agricultural Research

Table 1
Description of the single case studies used in the apple case study analysis.

Subcase study (#)	Initial objective	Requested from farmers	Activities and methods[a]	Involved stakeholders[b]	Results and implementation	Communication	Dataset
WebForm (1)	To create a new web-based forecasting system for the apple tortricid complex	Yes	NR	R, G, GO, C	A forecasting model was developed and implemented on a web-platform. The knowledge was introduced into the Agricultural board's booklet on IPM in apple.	PP PA EP	Sjöberg et al. (2015a)
OrgFarm (2)	To development pest management strategies in organic production in collaboration with farmers utilising complementary biological control	Yes	NR PAR FFS	R, G, GO, A	A monitoring system for apple sawfly was set-up for Swedish conditions and validated with growers. The optimization of application time for *Q. amara* was established. On-farm application of entomopathogenic fungi against the apple sawfly was shown not to be satisfactory under current orchard practices. Agroecological crop protection strategies were designed and knowledge gaps were identified for FFS and further scientific studies. Organic growers joined the crop protection lobbying group. Growers began to increase flower cover and monitoring in their orchards. The knowledge was introduced into the Agricultural board's booklet on IPM in apple,	PP PA EP	(Sjöberg et al., 2015b; Swiergiel, 2015; Swiergiel et al., 2016)
MMD-AFM (3)	To develop a new multipurpose mating disruption for the apple tortricids and a kairomone blend to monitor the AFM	Yes	NR PAR	R, G, A, C, B, GO	A new MMD formulation was developed for Northern European tortricids and registered in EU. A new kairomone trap was developed and made available on the market. The knowledge was introduced into the Agricultural board's booklet on IPM in apple,	PP PA P EP	(Knudsen and Tasin, 2015; Porcel et al., 2015)
Bioman (4)	To study the control by natural enemies over aphids and scales and the management factors affecting their biological control	Yes	NR	R, G	Key natural enemies for aphids and scales biological control were identified. Their seasonal variation and the impact of flower cover, sulphur sprays and soil tillage on the natural enemies was investigated. The knowledge was introduced into the Agricultural board's booklet on IPM in apple,	PP PA EP	Porcel et al. (2018)
Synbio (5)	To enhance pest resilience in orchards through a synergy between semiochemicals and conservation biological control	No	NR PAR	R, G, A	New kairomone blend to monitor tortricid pests were developed. New seed blends of local flower strip species were optimised for Swedish orchards. Flower strips were implemented and evaluated on commercial farms. A new biodegradable attractant for lacewings was set-up.	PP PA EP	(Giacomuzzi et al., 2016; Knight et al., 2019; Pålsson et al., 2019)
EcoOrchard (6)	To boost functional biodiversity in organic orchards	Yes	NR PAR FFS INT	R, G, A	Flower strips were shown to increase natural enemy presence and lower the presence of two major pests. New directions on the use of flower strips were developed. A manual on how to establish and manage flower strips was published. Monitoring of natural enemies by growers and advisors was tested and a manual was published. Advisor started FFS in monitoring of pests and natural enemies. The knowledge was introduced into the Agricultural board's booklet on IPM in apple.	PP P EP M	(Cahenzli et al., 2019; Penvern et al., 2019; Pfiffner et al., 2018, 2019)
EcoFruit (7)	To study the effect of management on ecosystem services for fruit production in different European climates	No	NR	R	Effects of orchard management and of local and landscape factors on predatory arthropod communities varied between regions Management influenced six out of seven predatory arthropod groups. Organic management was more efficient than integrated pest management in developing environmentally friendly apple orchards with higher species richness. There was no inherent trade-off between species richness and yield. Development of more environmentally friendly means for pest control, which do not negatively affect pollination services, was identified as a priority for sustainable apple production.	PP PA	(Happe et al., 2019; Samnegård et al., 2019)

[c](PP) peer reviewed scientific article, (PA) popular applied science for the sector, (M) manual, (EP) extension publication and grower seminar.
[a] (NR) natural science based research, (FFS) farmer field school, (PAR) participatory action research, (INT) semi-structured interview.
[b] (R) researchers, (G) growers, (GO) grower organisations, (A) advisors, (C) plant protection companies, (B) board of agriculture.

Table 2
Identified problems or challenges in the grower's implementation of IPM and how it has been addressed by the research projects (RP) in relation to the activity system elements (ASE) (Engeström, 2015).

Problem/challenge	Concerned ASE	Addressed by RP	Concerned ASE
Main pest problems: tortricids, apple sawfly (ASF) and apple fruit moth (AFM). - Inefficient control - Knowledge gap in biological cycle - Non-optimal timing of pesticide applications	Focus on tools: type of pesticides, biological cycles, timing. Subject. Lack of knowledge.	1) Forecasting (biological cycles, models, traps) for optimised pesticide applications against tortricids, apple sawfly and AFM. 2) Experiments with non-/low-toxic control methods: mating disruption of tortricids, *Beauveria bassiana* & *Quassia amara* against ASF.	Tools: forecasting and control methods. Division of labour: increased knowledge through project collaboration and communication.

(Stiftelsen Lantbruksforskning) (1,3,4) and by the Swedish Research Council for Sustainable Development (Formas) (2, 5–7). Project 6 and 7 were framed within the EU (CORE Organic Plus and BiodivERsA-FACCE2014-74, respectively). Additional support was obtained by SLU (Plant Protection Biology Department and Partnerskap Alnarp), by the Apple Growers Cooperative (Äppelriket) and by the Swedish Board of Agriculture (Jordbruksverket).

The stakeholders directly involved were apple growers (20) from the main apple production area in the South of Sweden (Skåne and Blekinge counties) and a minor apple production area further north (Västra Götaland), fruit and food company advisors (4), county board advisor (2), a board of agriculture advisor (1), researchers (5) and apple co-operative managers (2). These stakeholders represented active actors within both the organic and the conventional apple chains in Sweden, including large and small holders and two among the major actors on the apple Swedish market. The farms belonging to the involved farmers are situated in both agriculture and forest dominated landscapes. Within individual project field walks, training courses and stakeholder group meetings were organised (Table 1) to set-up an active dialogue with apple stakeholders and begin to implement the emerging strategies. Group meetings within individual projects followed an iterative PAR cycle. Suggestions for meeting topics were collected before hand and at the end of each meeting it was evaluated if the topics had been addressed. Meetings were recorded and notes were taken. Project 2 followed an iterative annual meeting cycle for three years where current pest management problems, possible solutions and research actions were discussed before each growing season and noted in an idea bank which was developed into an action plan. During the growing seasons meetings included field visits to farms and research experiments as well as farmer field schools. After each growing season the planned actions (in research and practice) were presented and analysed in the group. Project 2 also included two surveys and 10 interviews with the growers concerning their farms and perceived pest problems. All meetings and interviews within project two were recorded, transcribed and coded. Further details can be found in Lennartsson (2012), Neupane (2012a) and Swiergiel (2015). Surveys were performed and interviews were recorded, transcribed and analysed in project 6 (Penvern et al., 2019; Stranak, 2018). The case study narratives in this paper reach across all the mentioned projects and are based on the collection of data, student theses, dissertations and papers produced within these projects.

2.2. Case studies: research process and problem formulations

2.2.1. Case study 1: forecasting systems and semiochemicals

Fruit growers and advisors pointed out the need to improve the efficiency of the control of apple tortricids (*Adoxophyes orana, Archips podana, A. rosana, Cydia pomonella, Hedya nubiferana, Pandemis heparana, Spilonota ocellana*), apple sawfly (*Hoplocampa testudinea*) and apple fruit moth (*Argyresthia conjugella*), especially after the ban of several old chemicals and the introduction of less persistent and more selective pesticides. Specific information on the biological cycle was needed in order to optimise the timing for insecticide use. This information was required as a base to reduce the use of unnecessary sprays and to develop new plant protection products.

In Sweden, the ban of the last broad spectrum organophosphate azinphos-methyl occurred after 2008 (Sjöberg et al., 2015a). Research was carried out in project (1) by Sjöberg and co-workers to investigate the effects of the transition from a broad-spectrum pesticide to ovicidal or larvicidal compounds on tortricid management strategies. In this study, factors such as the temperature during winter and spring, the number and timing of insecticide applications, and usage of azinphos-methyl in 2008 significantly affected population size and damage caused by the complex of apple tortricids.

Following the study of Sjöberg et al. (2015a) and the setting of the forecasting model for tortricids, research was carried out to specifically set-up a new multipurpose mating disruption formulation (MMD) to regulate the species range of tortricid pests in apple (*A. orana, A. podana, A. rosana, C. pomonella, H. nubiferana, P. heparana, S. ocellana*) within Northern Europe (Project 3). A reservoir multicomponent dispenser was developed in co-operation with the companies CBC Biogard (Milan, Italy) and Shin-Etsu (Tokyo, Japan). As a complement to mating disruption, availability of a tool capable of precisely revealing the flight activity of females could allow for prompt prediction of moth attacks in orchards treated using mating disruption. To this aim, the attraction of new kairomone lures was tested in field trapping experiments.

The apple fruit moth *A. conjugella* moves from the forest to the apple orchard inflicting serious damage in certain years. Both Swedish and Norwegian growers were concerned about improving the sensitivity of available forecasting systems. A long-term study was conducted since 2008 in co-operation with Nibio in Norway to identify a volatile attractant to monitor movements of the pest from the forest to the orchard (Project 3).

The need to expand the available information on the apple sawfly (*H. testudinea*) and its control, particularly in organically managed orchards, emerged in 2010 during the annual apple meeting. Apple sawfly is a serious pest in European organic apple production causing up to 100% damage (Vincent et al., 2019). Larvae hatch during a short period only after which they enter and feed upon the apples, eventually overwintering in the soil. This life cycle makes correct control timing crucial (Graf et al., 2002). Furthermore, low impact alternatives to synthetic insecticides for the control of apple sawfly are scarce hindering pest management in organic apple orchards. Accordingly, project 2 was developed with a group of six organic apple growers and two advisors with the aim to co-learn how to sustainably manage the sawfly pest. This study involved the validation of a forecasting model and control of the sawfly using the botanical pesticide *Quassia amara* and microbiological control using the entomopathogenic fungus *Beauveria* *bassiana* (Bals.-Criv.).

Apple growers had expressed the need to learn how to prepare *Q. amara* extracts and time the application in order to achieve a higher control of the apple sawfly. This was addressed through laboratory experiments and exchange of experiences in the PAR group (Lennartsson, 2012; Neupane, 2012a; Sjöberg et al., 2015b).

Additional information concerning participating actors, methods, results and communication for each projects is presented in Table 1. When analysed with the help of the activity system elements the identified problems appear to belong to the subject and tools (Table 2). Similarly the research projects addressed the problems by developing tools that would increase the farmers knowledge and facilitate actions to improve the efficiency of pest control and reduce the negative effects of pesticides. Additionally the division of labor was addressed through the PAR approach.

2.2.2. Case study 2: conservation and enhancement of natural enemies

In two consecutive Äppelträffen workshops (2011 and 2012), apple growers and advisors remarked their perception of an increase in the incidence of aphid and scale pests in the previous years. Sudden outbreaks of secondary pests had prompted additional intervention primarily with chemical insecticides. The reasons underlying more regular and severe outbreaks were unknown, though the participants pointed towards the 2008 shift in insecticides that may have interfered with the beneficial arthropod community and thus the natural regulation of pests. The study of natural enemies of pests, and possible management strategies to foster their ecological service, was appointed as one of the research priorities. We intended to produce the knowledge required for the development of strategies to conserve and increase natural enemies of pests contributing to a better resilience of the orchard system. This work would thus provide knowledge on both the preventive and proactive aspects of conservation biological control in IPM.

In order to identify the key natural enemies, their seasonal distribution, and the impact of agricultural practices, aphid predators were collected through suction sampling in 2013 and 2014 and identified under a stereomicroscope following entomological keys. Some 15 samples were taken per orchard and date in 2013 and ten in 2014 following the methodology described in Porcel et al. (2016). In 2013, six organic orchards were sampled (three using sulphur for scab control and three totally unsprayed) and four orchards under IP for 15 consecutive weeks starting on May the 13th. In 2014, eight organic orchards were sampled (four sulphur-sprayed and four unsprayed) and six IP orchards for 18 weeks starting on April the 28th. In addition to natural enemy populations, the natural regulation exerted by these beneficial arthropods on aphids (Porcel et al., 2018) and scales (unpublished data) was measured by means of apple trees inoculated with sentinel colonies of *Dysaphis plantaginea* (Pass.) and *Lepidosaphes ulmi* L.

For the data presented in this paper, generalized additive mixed models (GAMMs) were used to dissect the effect of sulphur treatments on natural enemy populations and the effect of management on woolly apple aphid abundance. Additive modelling allows to model non-linear relationships between explanatory variables and the response variable, as for example the temporal oscillation in arthropod populations throughout a growing season (Porcel et al., 2017b). Mixed effect models are useful for the analysis of data collected in clustered units, such as orchards, and for measurements taken over time on the same experimental unit. A separate model using a Poisson error distribution for count data was built for each family of natural enemies and the pest, establishing treatment (sulphur-unsprayed or IP-organic), year and sampling date (modelled using a non-linear smoother function) as fixed factors. Orchard ID was included in each model as random effect and temporal autocorrelation was corrected by adding an AR(1) covariance structure. Wald tests were used for statistical inference of the treatment effect.

Predatory arthropod communities collected in IP and organic orchards in 2013 and 2014 were statistically compared using a two-way permutational analysis of variance (PERMANOVA). PERMANOVA is a multivariate test that allows to establish whether the distance between the centroids of groups is statistically significant (Anderson, 2001). Management type and year were used as factors after testing for equal multivariate dispersion using the function 'betadisper'. The analysis was based on the Bray-Curtis dissimilarity distance. The graphical 2D representation of the arthropod community was carried out by non-metric multidimensional scaling (NMDS) based on the Bray-Curtis distance. Data were transformed with a Wisconsin double standardisation prior to the analysis. Statistical analyses were performed with R version 3.4.3 using packages 'vegan' and 'mgcv'.

Growers and advisors participated in demonstration activities where pests and their natural enemies were identified in the laboratory and monitored in the field (Project 4 and 6, Table 1). They expressed a need to increase their competence concerning taxonomy and suitable monitoring techniques, particularly for natural enemies. Through the European research project 'EcoOrchard' (Project 6), specific workshops were organised to compare and discuss different strategies to enhance key natural enemies and monitor their biological control activity, such as functional diversity improvement, habitat manipulation in particular, and minimisation of ecosystem disturbance. Habitat manipulation consists of strategies to attract and improve the performance of locally occurring natural enemies in order to increase pest control (Nilsson et al., 2016). A specific habitat manipulation strategy was developed by the international research consortium and assessed in Swedish organic orchards. Perennial flower strips were designed, alongside a flower strip management scheme, for the alleyways between apple tree lines and evaluated in the field. The effect of organic farming, agro-environmental schemes and surrounding landscape on pests and natural enemies was assessed in co-operation with researchers from additional EU countries through Project 7.

Additional information concerning participating actors, methods, results and communication for each projects is presented in Tables 1 and 2 When analysed with the help of the activity system elements a similar patterns is found as for case study 1 (Table 3). Problems appear to belong mainly to the subject and object while the research project address tools and division of labor (Table 4).

2.3. Analysis of participatory development of IPM strategies

According to the Cultural-Historical Activity Theory (CHAT) a production activity is composed of six basic elements namely subject, object, tools, rules, community and the division of labour (Nuutila and Kurppa, 2016). For the sake of scientific clarity we will here introduce some CHAT terms. However, in this paper we choose to use common terms to facilitate for readers not familiar with CHAT.

The development of an activity is driven by tensions within and between the activity system elements. These tensions are called contradictions in CHAT terminology and can be understood as the root cause behind the problems and challenges (contradiction hypotheses) that appear while striving to reach the object. In this paper the subject is our research group, the activity is the development of IPM in Swedish apple production and the object is to reach an advanced IPM in practice (as defined in the introduction).

Table 3
Identified problems or challenges in the grower's implementation of IPM and how it has been addressed by the research projects (RP) in relation to the activity system elements (ASE).

Problem/challenge	Concerned ASE	Addressed by RP	Concerned ASE
- Increased incidence of aphid and scale pests. - Unknown impact of shift in pesticide use on natural enemies (NE). - Lack of knowledge on NE biological cycles.	Object: the increase of pests. Subject: lack of knowledge.	- Study on key NE in Swedish orchards and the impact of agricultural practices. - Collaborative learning and training: monitoring and enhancement of natural enemies.	Tools: scientific knowledge on key NE, monitoring, conservation and enhancement. Division of labour: collaborative learning and training

Table 4
Successes and obstacles towards the object of reaching implementation and advance IPM in practice in case study 1 research project.

Success (S)/obstacle (O)	Concerned AS
(S) optimization of a pheromone blend to control 6 species of tortricids in orchards	Tool, Subject
(S) identification of a new kairomone blend to monitor apple fruit moth attacks in orchards	Tool, Subject
(S) set-up of forecasting models for sawfly and tortricids	Tool, subject
(S) introduction of learning concerning pest monitoring into advisory material and field training.	Tool, Subject, Division of labour
(O) time and cost of pest monitoring	Tool, Division of labour
(O) time and cost of application of mating disruption	Tool, Rules, Division of labour
(O) compatibility of certain habitat manipulation with current orchard practices	Tool, Object
(O) lack of a shared goal between stakeholders limits the use of forecasting models	Object

Implementation of IPM in practice is a separate activity where the growers are the subject. Through research project case studies we investigated how this work is performed (division of labour) with different actors (community) and how it affects the six elements of the IPM development activity. We will use the model of an activity system in order to identify whether our participatory action research (PAR) work is contributing to the resolution of the identified problems and challenges in the growers IPM activity in apple and what is lacking in order to further strengthen its implementation in practice (the growers object) and advance the IPM practice (the object of our IPM development activity).

3. The development and current implementation of the IPM concept in Sweden

3.1. Development of IPM in Sweden

Work on action programs for reduced use of plant protection products started in Sweden in the pre-EU mid-1980s, a great deal earlier than the subsequent EU regulation (1107/2009). According to the historical account by Swiergiel et al. (2018), IPM became a necessity in Sweden after the rapid intensification of agriculture, which resulted in several undesired outcomes. For example, an increase in disease outbreaks such as the fruit tree canker (*Neonectria ditissima*) requiring additional fungicide applications. Similarly, from the mid-1980s, the use of pyrethroid insecticides led to severe secondary outbreaks of spider mites, due to the negative side-effect upon mite predators. Contemporaneously, resistance to pesticides evolved in several species, e.g. the pear psyllid. To address these problems, the agricultural authorities commenced extension-led IPM groups for farmers. After a decade of use, non-selective pesticides such as pyrethroids were replaced with IPM compatible compounds. This work was hampered during the 1990s when the number of state funded advisors was drastically cut. Furthermore, the IPM standards were lowered when the advisory services became dominated by private actors.

3.2. Current apple IPM in Sweden

The Swedish Board of Agriculture (Jordbruksverket) is the responsible authority for leading the monitoring and evaluation of the IPM work, but many other authorities are involved in the development of the prioritised objectives. The action plan has two focuses. Firstly, to bring the levels of plant protection products in surface and groundwater down to almost zero, ensuring low pesticide residues in domestically grown crops, safeguarding that safety measures are upheld to reduce exposure risks. Second to reduce dependency on pesticides by developing sustainable cultivation systems that include to a greater extent alternative approaches or techniques. The main implementation tools are training, information and advice. Monitoring pests in orchards is a prerequisite for the optimal use of plant protection measures. ‘Scab and pest forecast in fruit’ is a web-based decision support system providing information on the optimum time to spray and indicating on the following risk events for the most serious fruit pests. The forecast models are provided by the RIMpro forecast platform (Trapman, 2004). The service is free and available to the public as a part of the government-funded goal to reduce the risk and adverse effects upon health and the environment connected to the use of pesticides. For the many pests where forecasting models are lacking, early warning is given based on regular field observations and assessments. Plant protection data is gathered weekly from approximately 15 orchards and hundreds of samples are analysed and summarised in alert letters. Some samples require specialist knowledge or specific analyses. However, there are only two commercial plant pest diagnostic laboratories in Sweden, one of which is specialised on nematode analyses. A significant problem, and one shared by advisors in several European countries, is a lack of plant clinics and the general decrement of morphological identification skills competence and extension services. Growers practicing IPM lack competence and role in the decision-making, which are important components of the national action plan. There is a great need for information concerning fruit pest and natural enemy biology, control strategies, use of pesticides and their associated risks. The Swedish fruit industry is a relatively small sector with a limited number of researchers, crop advisors and plant protection advisors. Effective cooperation is necessary and actor's primary roles are often combined when it comes to applied research, demonstration projects, education of growers and advisors and disseminators of information. The Plant Protection Centre in Alnarp (Swedish Board of Agriculture) organises or takes part in courses, field excursions, telephone meetings, conferences and develops web-based and printed extension educational outreach material.

Direct action is an often-necessary last step in an IPM strategy. In recent years, several active substances have been developed and introduced whilst similarly many substances have been phased out. Although a number of plant protection products were deregistered because of their negative impact upon human health and the environment, other old chemical substances were not accepted due to a lack of data required to obtain product authorisation or approval renewal in accordance with the current Pesticide Regulation (EC) 1107/2009. Sweden belongs to the Northern zone that accounts for only around 3% of the market for plant protection products in Europe and is thus significantly less attractive to plant protection companies. Consequently, it has been increasingly difficult to get access to plant protection products in crops grown on a small scale (minor crops) or against minor pests.

In 2007, a national project ("Minor use") was launched to broaden the availability of plant protection products (including biological, chemical and low-risk products such as insecticidal soaps and vegetable oils) for minor uses. The majority of all applications for extensions of authorisation for minor uses (EG 1107/2009, art. 51) and applications for authorisation in emergency situations (EG 1107/2009, art. 53) are administered and funded by this project. Although almost all publicly funded research is focused on the development of alternative methods, an 'emergency situation' is still a matter of definition. The apple fruit moth *Argyresthia conjugella* (Zeller) is an example of a problem that Swedish fruit growers have for years been unable to contend with due to one-year emergency registration of insecticides. Consumer demand for products that are locally grown and labelled with a certification logo is on the constant rise. Certification opens up new marketing opportunities and the industry has introduced various certification systems. Integrated production (IP) is a standard for the certification for companies in the food and ornamental plant industry. Sigill Kvalitetssystem is the main operator that offers the largest standard for fruit and vegetable production in Sweden. The area of organic orchards is approximately 210 ha, which represents around 13% of the total fruit growing acreage. There is a great diversity in how organic orchards are managed ranging from highly extensive to densely planted, labour-intensive modern ones.

3.3. The shifting object of IPM in Sweden

In conclusion, while in theory the concept of IPM emphasises preventive pest management, in practice it mainly focused on crop protection tools which could decrease the negative effects of pesticide use. Avoiding or managing the build-up of resistance and secondary pest outbreaks, are emphasised in the farmer IPM object. This is combined with the EU and state driven emphasis to decrease environmental and health effects of pesticides. The toolbox has increased with time from using less or non-toxic pesticides to include monitoring and threshold values as well as a pedagogical component of learning from the evaluation of monitoring, measures and results. While in theory the object of IPM is growing in complexity involving the sustainability and redesign at the whole farm approach, in practice it is still struggling to achieve sufficient diagnostic skills, monitoring tools and registration of both conventional and low-toxic pesticides.

4. Results

4.1. Case study 1: forecasting systems and semiochemicals

Sjöberg and co-workers investigated the effects of the transition from a broad-spectrum pesticide to more specific insecticides on tortricid control. The results revealed that the number and timing of spray applications did not change after the shift in pesticides. Hence the ban alone did not initiate a development towards a more sustainable agroecosystem management practice. Furthermore, there was an increase in damage at harvest leading the authors to conclude that a higher precision in insecticide application was needed (Sjöberg et al., 2015a).

Based on these results, a forecasting model was developed to predict the time of emergence and the population size of the seven tortricid species concerned. The final phase of the validation of the model is on-going with the aim to provide growers with a friendly web-based platform.

Following the study of Sjöberg et al. (2015a) and the setting of the forecasting model for tortricids, mating disruption (MMD) was tested to regulate the species range of tortricid pests in apple. The new formulation showed a comparable or higher efficacy than the standard chemical treatment in the control of the tortricid species (Porcel et al., 2015). Whilst species such as *Archips* sp. and *C. pomonella* were kept under control by the new dispenser, the efficacy towards *S. ocellana* was rather more variable, with unexpected outbreaks occurring specifically in organic orchards. An increased performance towards *S. ocellana* was achieved in 2014–2015 by increasing the content of a secondary pheromone component of this species via continued collaboration with the companies (Porcel et al., 2017a). The improved MMD kept the damage at 4% in comparison with 16% in the control. While the surface covered by MMD increased from 22 to 80 ha during 2012–2015, the use of curative insecticides decreased to zero under the same period. A considerable number of the growers involved in this multi-actor project expressed their interest in using this device as soon as it passed country-specific registration hurdles. In order to maintain growers' trust in the new MMD, orchard damage scouting needs to be performed in order to inform growers whether disruption is working sufficiently or a pesticide application may be required in specific parts (Table 4). Presently this new dispenser is under evaluation for registration within the EU. As reported earlier, current long-timescales and high costs for EU registration of such low-risk plant protection products, combined with the cost and time of damage scouting, may delay implementation.

Unexpected attacks of the apple pith moth *Blastodacna atra* were registered in some of the orchards at pre-harvest. Monitoring of this pest needs to be set-up in order to time a possible intervention. In 2013, such an intervention was required in 15 over 33 MMD hectares to keep fruit damage at an economic level.

Additional information on the flight activity of tortricid species was collected in 2016–17 through delta traps loaded with new blends of plant and microbial volatiles. Depending on blend composition, a different ratio of both sexes of *C. pomonella, H. nubiferana, A. rosana, P. heparana, P. cerasana and S. ocellana* were caught (Giacomuzzi et al., 2016; Knight et al., 2019). Additional blends are currently under evaluation.

The study on the apple fruit moth *A. conjugella* was successful and a blend was patented (Knudsen and Tasin, 2014). Through the use of such a kairomone trap, we could localise the areas under attack and accordingly restrict the use of insecticides solely to the affected part of the orchard (Table 4). Some of the growers participated actively in this monitoring activity and learned how to use the traps, how to recognise the pest and how to apply the associated economic threshold (Knudsen and Tasin, 2015). Additional research on the basic mechanisms behind apple fruit moth attraction to plant volatiles were described (Knudsen et al., 2017). Further implementation of this monitoring system is limited by socio-economic factors. Presently neither single growers nor their associations are willing to assume the cost of trap scouting. However, a new company has recently placed this product in its catalogue and it is now available on the market.

Due to the lower number and often limited efficacy of the available plant protection products in comparison with IPM programmes, organic farming (OF) offers a platform to explore the validity of unconventional tools as plant protection products that might possibly be subsequently incorporated into IP (Marchand, 2018; Matyjaszczyk, 2018). As noted by Miñarro and Garcia (2018), low input orchards offer the opportunity to study natural mechanisms regulating crop pests, because of the low disturbance from pesticides. Accordingly, we incorporated part of our co-learning activity with organic apple growers as a support to the development of sustainable IPM strategies. When moving from the laboratory to the field, Świergiel et al. (2016) found that the high mortality of apple sawfly due to fungal application demonstrated in the laboratory study was not confirmed in the field. In addition, *B. bassiana* application in organic orchards resulted in densities above the upper natural background level during the growing season, although reversion to background levels occurred within a year. Further work is needed to identify factors possibly affecting the efficacy of *B. bassiana* in sawfly control, such as soil humidity, application technique and sulphur as fungicide.

Field trials were conducted in orchards in order to measures the efficacy of the *Q. amara* extract applied according to different timing. Although the highest pest control was achieved in plots treated according to a cumulated temperature model, we found that growers without access to a nearby weather station for local temperature sum calculations could still use petal fall to time their *Q. amara* application. Additional information on the effect of extraction technique upon quassin and neoquassin levels from *Q. amara* wood chips and their storage stability was also collected (Neupane, 2012b). Organic growers were very interested in improving application timing of *Q. amara* extract particularly since it is able to efficiently control aphids with the same application. Presently, since 2013, *Q. amara* is still awaiting a new safety evaluation and registration within the EU countries. Available forecasting models to predict the phenology of the apple sawfly were thus validated for Swedish conditions (Lennartsson, 2012; Neupane, 2012a; Sjöberg et al., 2015b).

An analysis of the activity system reveal that most successes belong to the tool element while obstacles to a higher extent are attributed to other elements such as the division of labour, rules and object (Table 4).

4.2. Case study 2: conservation and enhancement of natural enemies

Unsprayed and organic orchards presented a higher diversity and abundance of natural enemies of aphids and scale insects over a two-year period as compared with IPM orchards (Fig. 1). Differences were observed for management type (PERMANOVA, $F_{1,\ 23} = 3.74$, $P = 0.007$) and year (PERMANOVA, $F_{1,\ 23} = 6.66$, $P = 0.001$). Predatory bugs (Anthocoridae and Miridae) and brown lacewings were the families of predators most associated with organic management whilst in IPM orchards, the dominance in the predatory community shifted towards spiders and *Anystis* sp. mites (Fig. 1).

The effect of pesticides on predatory bugs impacted clearly upon the biological control of the rosy apple aphid (Pålsson et al., 2016; Porcel et al., 2018). *Anthocoris nemorum* (L.) was shown to be a key natural enemy in Swedish apple orchards contributing strongly to the early suppression of aphids both due to its timing and its apparent prominent prey location capacity (Porcel et al., 2018). Changes in abundance of this predator are likely to influence biological control of aphids to a great extent. The regular spray of sulphur in organic orchards did not have an observable impact on

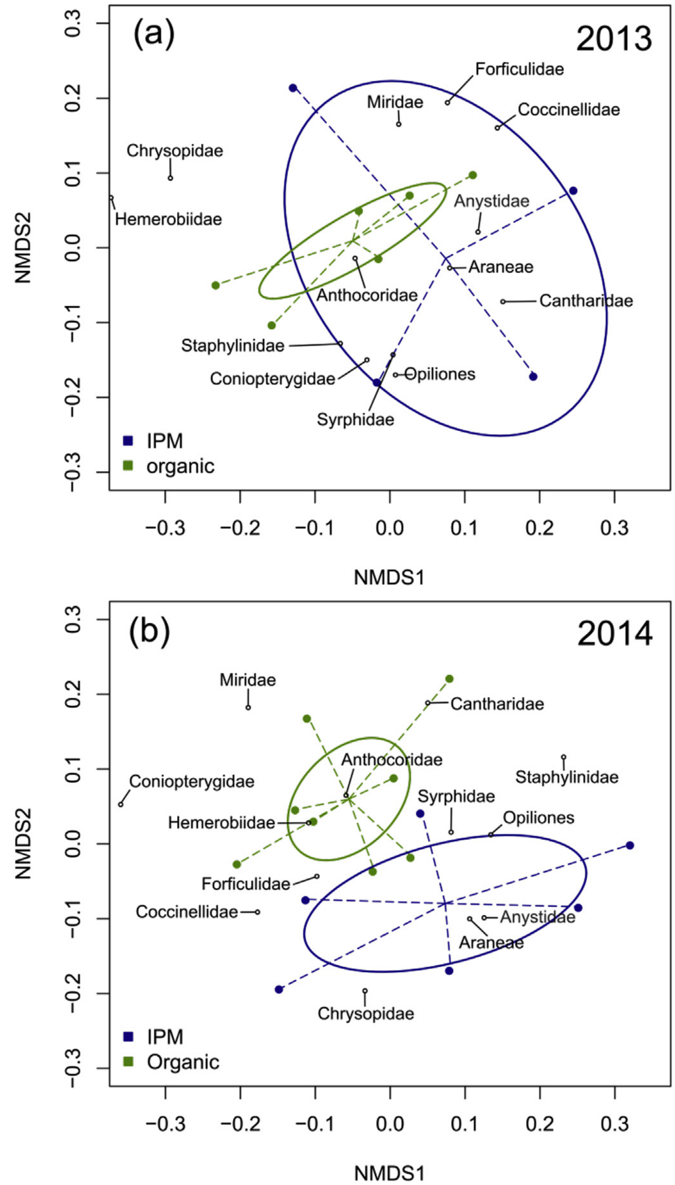

Fig. 1. Non-metric multidimensional scaling (NMDS) graphical representation of the predatory arthropod community in organic and IPM orchards in (a) 2013 (Stress = 0.31) and (b) 2014 (Stress = 0.14). Orchards under the same management are connected by dotted lines that intersect at the centroid of each group. Ovals represent the standard deviation of the groups.

predators (Fig. 2). Only ladybirds seemed to be affected negatively while the rest of predators had a high variation in both sprayed and unsprayed orchards that resulted in no significant differences (Fig. 2). Although sulphur had very little impact on the natural enemy community, its use resulted in almost total suppression of *L. ulmi* in orchards indicating a powerful direct effect upon the pest (Porcel et al., unpublished). Woolly apple aphid presence was only recorded in significant numbers in 2014 in pesticide-sprayed orchards (1.71 ± 0.28, mean individuals per sample ± SE), associated with low levels of natural enemies, as compared to organic orchards (0.09 ± 0.03) (GAMM, Wald test, $P < 0.001$). This fact suggests that in Swedish conditions the pest can be naturally regulated. *Aphelinus mali* (Hald), introduced to Sweden in the 1940s as a classical biological control agent, was detected in all orchards where *E. lanigerum* was present, with mean parasitism rates

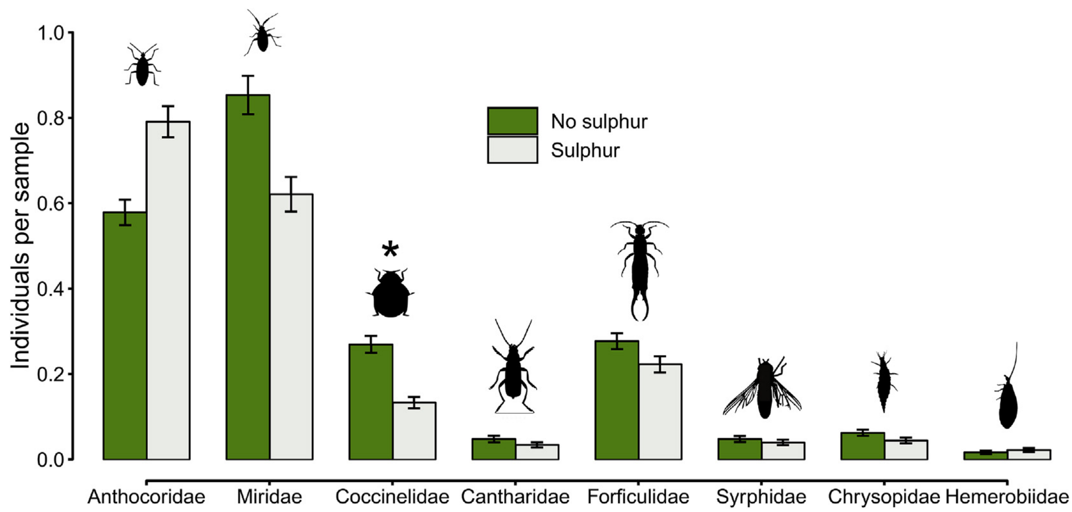

Fig. 2. Comparative of sulphur-sprayed and unsprayed organic orchards on common predator abundance (Mean ± SE). * indicates statistically significantly different values (GAMM, Wald test, $P < 0.05$, Table S2).

ranging from 30 to 70% (Porcel et al., unpublished).

Habitat manipulation, such as cutting every second row of grass between the apple trees to preserve natural enemies, and saving flowering plants around and in spots within the orchard spread during the time of the research projects (Penvern et al., 2019). One farm introduced flower strips in all newly planted apple and cabbage fields. The monitoring method of natural enemies was optimised together with growers and advisors and is now introduced into advisory material and a one season field training was performed (Table 5). With respect to grower's experiences from the PAR work and their perceptions on habitat manipulation, the lack of updated pest threshold values that include the natural enemy impact, as well as the limited knowledge and time for monitoring were stated as important limiting factors that need to be addressed by advisory services. Growers also identified as a limitation the scarce scientific information regarding the efficacy of habitat management, and asked for such strategies to be compatible with current orchard structure and management practices (Stranak, 2018; Waara, 2011). These compatibility aspects have been under consideration in project 6 (Table 5).

In addition, to advance the sustainable management of orchards, effective alternatives to systemic insecticides for the control of pests, such as the rosy apple aphid and the apple sawfly, are required. These compounds are most likely responsible for the depletion of the omnivorous natural enemies recorded in IPM orchards (Anthocoridae and Miridae in Fig. 1). IPM growers still rely heavily on these insecticides and regard their avoidance as risky, given that the pests targeted can cause severe damage levels (Happe et al., 2019; Samnegård et al., 2019). Additional research on the combination of flower strips and natural enemies attractant is on-going in our group (Pålsson et al., 2019).

5. Discussion

IPM is often described and approached as a set of pest management tools to be performed exclusively at the farm (Fig. 3, left panel) (Ratnadass and Barzman, 2014; Young, 2017). The aim is to develop knowledge about how to protect and benefit natural enemies, how to monitor and forecast the needs for action and finally direct increasingly efficient control measures that should minimise environmentally detrimental actions. However, is the focus on increasingly more efficient tools enough to make IPM the prevalent practice? How might we make IPM research relevant, desirable and applicable in practice? As shown in this paper, research focussing exclusively on tools will most probably only reach implementation if the tools do not require additional work or costs for growers and advisors. We reflect here that in order to advance the IPM activity, the activity should rather be seen as composed of a number of elements, as illustrated in Fig. 3, right panel. Although the IPM toolbox represents one of them, we need to take into consideration the interplay among all the elements when developing new tools. In our participatory IPM research work we have strived to increase our competence to include not only the natural science aspects but also the social conditions and new collaborations, a new division of labour, needed to develop and spread IPM, as reported in other sectors (Fulcher et al., 2017) including the wider agroecology with a food system perspective (Gliessman, 2015).

As a general background, the necessity to improve the efficiency

Table 5
Successes and obstacles towards the object of reaching implementation and advance IPM in practice in case study 2 research projects.

Success (S)/obstacle (O)	Concerned AS
(S) identification of key natural enemies (NE) and their seasonal occurrence in Swedish apple orchards.	Tool, Subject
(S) identification of the impact of production system, synthetic pesticides and sulphur on natural enemies	Tool, Subject
(S) introduction of learning concerning NE monitoring and enhancement into advisory material and field training.	Tool, Subject, Division of labor
(O) time and cost of monitoring	Tool, Division of labor
(O) time and cost of certain habitat modification measures	Tool, Rules, Division of labor
(O) compatibility of certain habitat modification with current orchard practices	Tool, Object
(O) effective alternatives to systemic pesticides against pests such as aphids and apple sawfly are needed in IP orchards to permit enhancement of natural enemies.	Tool

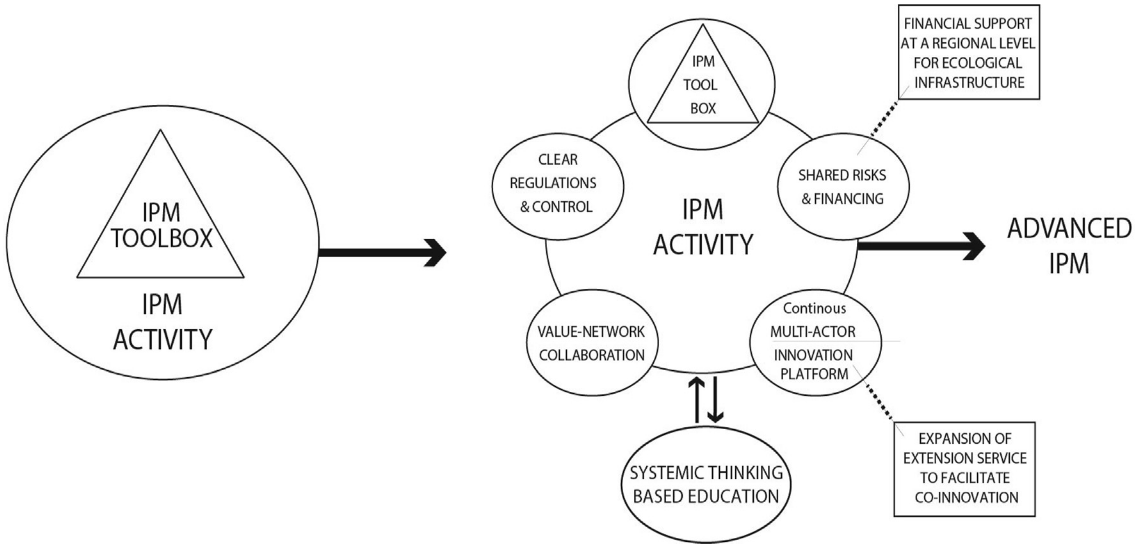

Fig. 3. Perceived IPM models. (Left) The earlier IPM activity model represented the previously hegemonic focus on the agronomic, technical and biological knowledge behind the development of tools in IPM research. (Right) The proposed model is composed of a number of elements, where the IPM toolbox represents one of them.

of the IPM tools can be linked to increasing competition within the global market. This mechanism has strongly contributed to the historic and currently extensive number of farmers having to leave agriculture (Eurostat, 2015). By communicating added values and trust in products and production processes, through for example certification and brands, products can be sold for a higher price on niche markets (Buurma and van der Velden, 2017). IPM however, is obligatory in Europe and as such encompasses all of agriculture and all consumers independently of whether they care for the environment and their health or indeed can afford more expensive food. Only very few producers are thus able to increase prices to cover any extra costs associated with particular IPM practices (such as an increased functional agrobiodiversity) by communicating the associated added value. Alternatively, the first adopters of any innovative technique, which reduces their costs (or alternatively achieves a higher product price after communicating the new added value), may increase their profit until the technique permeates through to the rest of the farmers and the prices are again driven down through competition (Ward, 1993). This leaves growers with two options in order to remain competitive. They can avoid the specific IPM practices that require additional costs or risks (e.g. flower strips) as long as adoption is not legally mandated and not required by the majority of the consumers, or, they need to continuously cut costs in other ways. Thus in order to survive in the market the majority of the producers need continuous innovation to keep costs (especially labour), lower or comparable to competitors. This suggests that IPM methods must strive to be efficient which supports our research focus on IPM tools. On the other hand practices that imply higher costs/lower profit in order to avoid negative environmental and health effects need to be financed by selling them as for example a tourist service (biodiversity) or via mechanisms other than simple free market competition such as subsidies or closer relations with consumers. This points to a lack in our research approach since some of the developed and desirable tools need to be supported by a modification in rules and division of labour elements as well as in how the wider socio-economic system (activity system network) is organised. Not including these aspects in research appears to turn the necessary implementation tasks to orphans. In other words, there is often a strong contradiction between short-term profitability and certain IPM tools that promote environmental and human health, which will not be solved by a single focus on the development of tools.

In our participatory research within apple IPM we have experienced that practices requiring limited additional labour whilst providing higher security to the production, are easily adopted by growers. The MMD is a typical example. Two conditions are crucial for a wide adoption of this technique; a commercially available product and an organised monitoring service throughout the season. Both issues relate to the division of labour; who is willing to take on these tasks and how should they be organised. In order to reinforce the trust of producers in the newly adopted MMD, advisors need to be in place to warn growers in case pest thresholds are reached. This suggests that new economic thresholds need to be developed and that the task of field monitoring necessitates to be learnt and carried out by growers with the initial support of advisors.

Although the availability of semiochemical-based control methods has significantly increased over the last two decades, their adoption is still very limited, due to the lack of time or opportunities to learn how to perform diligent monitoring. Many growers and advisors also feel that they have no time to check an increasing amount of monitoring devices such as traps, whilst others are content with their standard practice (i.e. insecticide), which does not require monitoring or a specific training. A rather direct answer again relates to the division of labour, namely to increase the number of advisors so that the current monitoring service could be expanded. Besides monitoring of pheromone-treated orchards, the new roles of these advisors could include the organisation of farmer field schools to co-innovate knowledge on how to estimate pest density and population level of beneficial insects and how to protect and enhance biological control. This is a role which was taken by the researchers in these projects. For the practice to spread and continue beyond the research project this role needs to be institutionalised. In connection to this, the development of online applications for field monitoring of pests and natural enemies could provide a long-term database to support both the advisory services and the IPM research (Lamichhane et al., 2016). Because the trend has been to reduce the number of state financed advisors since the 1990s without an equivalent increase of private advisors, a new national policy is probably required to achieve the above proposed objectives.

The second issue relates to the availability of the plant protection products on the market. Due to the high costs of safety evaluation and multiple EU zone registration costs, companies prefer to register products that are interesting to a large part of the EU grower market, or register only in some zones in order to receive higher returns on their investments. This makes it difficult to register products adapted to more local conditions such as the MMD, which includes the pheromone components of the tortricid species *S. ocellana* (an important pest in Northern European orchards). The same applies to pesticides with a more restricted use to organic growers, such as *Q. amara* and plant-based oils. Whilst at the European level a support to the registration of low-risk plant protection products is provided by the Regulation 1107/2009 EC, it seems that at the local level such support is lacking. We suggest here that a dedicated measure from local authorities with the aim to support safety assessment of new candidate products would substantially help spreading the use of low-risk plant protection means at the regional scale (Fig. 3, right panel). Encouragingly, to partially remediate this, apple growers in Sweden have organised themselves into a plant protection group, to communicate their requests to the Swedish authorities. This shows a step towards reorganizing the division of labour in favour of the implementation of practices collaboratively developed in the participatory research projects.

Beside the need to increase the availability of environmentally friendly IPM tools, growers expressed their interest to learn more about how to protect and enhance natural enemies. There is almost a complete lack of threshold values including information about how to adapt the pest threshold in the presence of a certain type and quantity of natural enemies. This is partially due to the complexity of the arthropod community of the orchard, with trophic interactions being shaped by seasonal and environmental variables. Modelling these interactions is a tool-focused solution which would require a considerable amount of currently non-available time-series data. In the lack of scientifically determined thresholds, the growers wish to learn more about the biology of natural enemies, their lifecycles and temporal occurrence in the field. This solution shifts the attention to the grower (subject) and training (division of labour). With the help of this knowledge they may find ways of avoiding harm to natural enemies or indeed provide them with resources to enhance their efficiency. With respect to this, farmers take a financial risk when they decide to replace a conventional method (usually a pesticide) with consolidation of conservation biological control. The risk is exacerbated by our partial understanding with respect to the multi-trophic interactions at the pest-beneficial interface. To bridge this knowledge gap, both in science and practice, the researchers behind this paper collected data from commercial orchards and developed simple monitoring tools along with growers and advisors. Although results were promising as seen in other IPM participatory contexts (LeBude et al., 2017), we find that this kind of applied action research and learning activity is often difficult to finance since it falls outside the definition of both research and development for a number of funding bodies. Additionally, the time spent on stakeholder interactions reduces the time dedicated to scientific publication, which currently remains in essence the sole metric of academic merit. It appears that the societal task of bridging applied research with its implementation in practice is lacking both financial support and institutionalisation. As researchers in Sweden, we experienced a fragmented and rather erratic support to applied plant protection research from public financiers. In comparison with other EU countries, we see a gap in the national policy with a view to develop long-term sustainable solutions for plant protection challenges. Hence, there is an asynchrony between the state object of research contributing to the development and implementation of advanced IPM in practice and the rules element, which would support the necessary merits from, and financing of, PAR work in research.

Habitat manipulation to enhance natural enemies is often not only knowledge intensive but also labour and land intensive whilst at the same time gives highly variable results in pest control due to different factors. Swedish apple growers experienced a constant dilemma between wishing to protect and enhance natural enemies and the risk of avoiding a pesticide application at the right time to prevent large harvest losses. This decision is made even more difficult since advisors often have limited competence within this particular field. Similarly, the decision to dedicate labour to establish and manage agroecological infrastructure instead of crops is difficult to make if there is a perceived lack of knowledge and guarantees that it will pay off via lower harvest losses due to pest suppression or reduced costs of additional pest management interventions (Stranak, 2018). Subsidising agroecological infrastructures and including it in advisory services, would share the responsibility for a safer environment and a healthier food with the farmers (Fig. 3, right panel). This would require a shift in the object of the agricultural policy and the advisory services. Fortunately, there are certain habitat modification practices which may require advisory support but little or less work on the farms such as not spraying the hedges, leaving organic material as shelter for natural enemies, alternating cutting of grass lanes to maintain shelter, provision of nectar and pollen resources and diversifying the wind break hedges (Pfiffner et al., 2018). These methods do however not provide enough pest control to maintain profitability in the majority of farms and need to be integrated alongside dedicated measures (Swiergiel, 2014). Whilst subsidies for certain biodiversity increasing measures have been promoted for many years within the EU (Primdahl et al., 2003), their impact on ecosystem services and yield in apple production is still under evaluation (Albert et al., 2017). A framework for improving the rationale to manage multifunctionality in agro-ecosystems which takes into account farmers' decision rules was recently proposed as a tool to help filling these kind of gaps (Martin and Isaac, 2018). In addition to these measures, we found that organic practices clearly contribute to a reduction of the disturbance and enhancement of biological control (Porcel et al., 2018). Because of the current growing demand of organic products by the Swedish consumers, we foresee the expansion of organic apple production as a possible way to increase the sustainable agroecosystem management and ecosystem service in the landscape (Samnegård et al., 2019). However, this is supported by the premium prices on organic products and would require a different rationale if it is to move from being a niche to the mainstream production.

The need to move beyond the focus on pest management tools to include other elements of the activity system is supported by literature. In Denmark the pesticide use in crops was successfully reduced from 1989 thanks to national pesticide action plans, pesticide taxes, national pest monitoring and threshold value development, experience-based growers groups assisted by advisors and single farm plans developed and evaluated together with advisors (Kudsk and Jensen, 2014). However, pesticide use is nowadays increasing once again in Denmark. The authors identified the main driver in the concentration of land to fewer growers and their preference to invest advisory cost in their own farm rather than meeting in other farmers' fields and learning together in groups. Detailed field inspections have been shown to greatly improve the ability to reduce pesticide use through threshold sprays, although a number of biological studies are still necessary for reliable forecasting and warning systems since this information often is lacking. A major limitation to implementation is the high cost of inspection, which exceeds the gains in pesticide reduction.

Barzman et al. (2015) presented several European cases where collaborative networks between growers, growers-advisors, and growers-advisors-researchers have achieved improved monitoring and reduced pesticide use with maintained or increased profits and reduced advisory costs. Typical for these collaborations is that the role of the participant changes. Advisors do not only prescribe management recipes to growers. They also coordinate collaborative learning and development. Growers are performing experiments and sharing their knowledge between themselves and with advisors and researchers. Researchers collaborate directly with growers and advisors in many or all research stages such as problem formulation, experimentation, analysis and result communication. Additionally, they contribute to the process of implementation and institutionalisation of IPM practices. The role of social learning through the facilitation of growers networking was positively associated with the early adoption of innovations, such as enhancement of the pollination service in agroecosystem management (Garbach and Morgan, 2017). Hence further research on, and implementation of, collaborative and adaptive management of food systems has the potential to foster the implementation of old and new research IPM tools that have not been successfully integrated into practice.

The earlier IPM activity model represented the previously hegemonic focus on the agronomic, technical and biological knowledge behind the development of tools in IPM research. Since the implementation rate of research results over the years has not been satisfactory, it has become increasingly apparent that tools cannot be developed in a vacuum. Instead they need to be co-evolved with the surrounding context in order to become desirable and feasible. To facilitate this, we propose a new model of the IPM activity, which includes the different elements that IPM depends upon. We suggest that all these elements should be considered in collaboration with relevant actors at some points of the research process in order to advance IPM in practice. Furthermore, based upon our analysis, we provide some concrete examples (dotted lines) of what these elements could be designed in future advanced IPM. While a full contradiction analysis was outside the scope of this paper, it could provide further knowledge whether the "root causes" of the problems are being addressed by the proposed model in order to find long-term sustainable solutions.

Several authors emphasise the need to include a whole system approach in current higher education programs for sustainable production (Barzman et al., 2015; Eksvard et al., 2014). Although in Sweden pest management education is based on the IPM approach, we recognise the need to teach the competencies required for a real change of role of farmers, advisors and researchers. Topic such as facilitation and coordination of collaborative networks, interdisciplinarity, understanding of the complex interactions in farming activities, farm-trial set-ups with collaborative evaluations could be considered to this scope. We anticipate that through such an agroecological approach, students will develop the capability to contextualise plant protection issues within a wider farming system perspective. By deeply understanding the root causes of recurring problems and by applying system thinking, students are expected to further develop their competence in both social and natural science (Fig. 3) (Francis et al., 2011).

The participated research activities with stakeholders combined to form a total of 97 published deliverables and 41 social activity output and meetings. Workshops, annual meetings, farming schools, seminars and other meetings accounted for 29,7% of the output, whilst manuals, peer-reviewed publications, popular press articles, patents and other publications accounted for 59,4%. Supervision work with undergraduate and post-graduate students accounted for 10,9% of the deliverables (Table S1).

6. Conclusion

As a general reflection, we further argue here that the eight IPM principles need to be widened to address the other elements of the activity system, particularly the rules and division of labour. This necessitates the inclusion of the wider social, political and economic aspects of implementing IPM. This is corroborated by the result from our participatory work and historical analysis, from which we conclude that the perceived need to apply potentially harmful direct and reactive pest control measures will not depend solely upon the efficiency of the preventive control strategies and the traditional transfer of technology model. The value given to more socially and environmentally friendly production standards such as IPM has transformed into political decisions, consumer choices and risk management strategies, which create more or less favourable conditions allowing replacement of potentially harmful plant protection programs. We recognised that in our region, a sustainable agroecosystem management with feasible and desirable IPM strategies could not be developed by focussing exclusively on the efficiency of the innovative plant protection tools because the cost-effectiveness and thus the implementation of such tools varied greatly with the simultaneous co-innovation of the socio-technical system. When the technical efficiency of new low-impact plant protection tools has been proven, their implementation in practice depends on factors such as the social context, the local values and the commitment of the involved stakeholders to make it work. Local stakeholders such as farmers and their associations, regional governments and consumer organisations should thus harmonise their vision and standpoints in order to set long term socially and environmentally sound objectives as a base to promote, finance and use new plant protection strategies within the Skåne region.

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Appendix A. Supplementary data

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