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Foreword

During recent years (2009–2014) 100 MSEK has been invested in more than 100 research projects addressing various issues within the field of integrated pest management (IPM) in agriculture. The calls for project proposals from the research community have mainly been launched by The Swedish Farmers' Foundation for Agricultural Research (Stiftelsen Lantbruksforskning) and to a lesser extent by the Swedish Board of Agriculture (Jordbruksverket), with a goal for short-term implementation in the agricultural sector. Project results have generated a large body of valuable knowledge and led to the publication of several reports and scientific articles. IPM is a broad concept that includes many aspects ranging from pest biology, to any sort of preventive, optimized, and alternative control methods used in agriculture. The foci and methods used in the studies therefore vary considerably, which makes the drawing of general conclusions and the analysis of implementation difficult. In view of this, and to identify needs for future research calls, Jordbruksverket contacted Stiftelsen Lantbruksforskning with a request to carry out a coherent review and synthesis of the results that hitherto have been accumulated.

This synthesis work also provides tools to create a platform for future research and extension endeavours within plant protection. References are also made to research performed in other European countries and conclusions from the recent analysis of IPM research across Europe. This appears as a very important point since regulations and recommendations within the IPM-area are made on both European and national levels.

The present report has been compiled and written by Research Officer, Dr. Eve Roubinet with support from a reference group consisting of Prof. Riccardo Bommarco at SLU, Administrative Officers Carina Carlsson Ross and Alf Djurberg at Jordbruksverket, Prof. Erland Liljeroth at SLU, and Plant Protection Expert Agneta Sundgren at the Federation of Swedish Farmers (LRF).

An impressive amount of information has been compiled in the present synthesis report. The receivers of the information will most probably be found among academics, extension specialists, civil servants, and interested farmers. Well received, the report will have an impact on both agricultural practices and future research and hopefully promote productivity in a sustainable way.

Stockholm, 17/08/2017

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Executive summary

Integrated pest management (IPM) is defined by the European Union¹ as the careful consideration of all available plant protection methods and subsequent integration of appropriate measures that discourage the development of populations of harmful organisms and keep the use of plant protection products and other forms of intervention to levels that are economically and ecologically justified and reduce or minimise risks to human health and the environment.

To support a successful implementation in Sweden, IPM has been a specific focus of research calls launched by Stiftelsen Lantbruksforskning and Jordbruksverket during the period 2009–2014. During this period, a total of 110 studies with IPM focus for an overall budget of over 100 MSEK were granted funds by Stiftelsen Lantbruksforskning and Jordbruksverket, mostly by the former. These studies form the basis of this synthesis report. This report is intended to evaluate the quantity and quality of research generated by these studies related to the overall aim of the investment, identify successful projects, and serve as a basis for future research calls and research programmes targeting IPM. The research calls launched by Stiftelsen Lantbruksforskning and Jordbruksverket and the bibliographic outputs of the granted studies are first described (I), and the findings of the studies are compiled (II). The four major pest/crop systems studied are then analysed in depth (III). In section III, each pest problem is introduced, the research projects and their outputs are described in detail, and the needs for future research are compiled. Result implementation in practice is finally discussed based on questionnaires and interviews with researchers and advisors. Concluding remarks and the compilation of future directions for research conclude this synthesis report (IV).

The overall aim of the research calls launched by the two funding bodies was to support research and development (R&D) projects of high relevance for the agricultural sector, with potential for rapid implementation within three to ten years. Stakeholders were involved in defining prioritised research areas, and, in the case of Stiftelsen Lantbruksforskning, in the project selection procedure. The foci of the calls were, in general, broad and covered the multiple facets of IPM in all farming systems. Thus, the studies included in this report varied largely in terms of scope. They targeted distinct aspects of the knowledge chain and, in some cases, led to product development. Some compilations of existing knowledge were also included.

A majority of the allocated budget (67 %) supported studies that targeted IPM in major economic crops such as cereals, potato, oilseed rape, and sugar beets. Studies of *Fusarium* in cereals occupied 30 % of this budget. Weeds in annual crops, *Phytophthora* in potato, and beet cyst nematode (BCN) in sugar beet occupied another 19 %, 13 %, and 5 % of the budget, respectively. Another 27 % of the total allocated budget financed IPM research in other crops such as forage crops, horticultural crops and willow production. Overall, studies set in major crops targeted a single aspect of IPM; e.g., single pest, single crop and over a limited time, with emphasis on harvested yield with a reduction of inputs. Projects in horticultural crops were generally performed in close collaboration with farmers and some used a systemic approach to IPM. In these cases, multiple pest and multiple aspects of IPM were investigated; such as preventive methods, development of alternative control methods – particularly biological control- and incentives for implementation. The outputs of the projects were variable in terms of scientific results and dissemination channels. To date, 24 % of the projects have published at least one peer-reviewed article with an average of 0.41 publications per project and 0.29 publications per MSEK granted. A single patent has been filed. The low rates of scientific publication and innovation might partly be explained by the small size of many projects. Furthermore, the 'mission' type of projects performed by advisory services or field trials might also explain that international publication has not been the primary focus of the projects. It may also reflect that some project leaders had no

¹ Art. 2.6, EU-directive 2009/128/ec, European parliament (21 October 2009)

previous experience in international peer-review publication. The financed projects have additionally generated the publication of 4 doctoral theses, one of which was done as partnership between university and industry, and 15 undergraduate theses.

IPM-research projects with successful implementation were identified. For instance, projects within the large programme BioSoM, coordinated by SLU in collaboration with advisory services and industry, and co-financed by Stiftelsen Lantbruksforskning, have resulted in commercially available analyses of soilborne pathogens. This illustrates the potential of coordinated programmes for implementation in practice. Another example is the successful development of a kairomone to monitor fruit moth in apple orchards, which has the potential to drastically decrease insecticide use. This innovation was also part of a larger collaborative programme that aimed at developing integrated control strategies against insect pests in orchards. Results from projects within cereal and potato breeding programmes were implemented in ongoing R&D programmes (public or private). Generally, many projects were followed by new, successfully funded research projects. In some cases, initiatives such as variety trials with focus on resistance characteristics were assimilated into national trials. The communication to advisory services of research results with potential for direct implementation was generally successful, with an integration of research results into advice published for farmers. The rate of adoption of this new advice by farmers was investigated for the four case studies and was found to vary according to cropping systems and type of advice. The use of tolerant cultivars and soil analysis to prevent BCN in sugar beet cultivation has been quickly and successfully implemented whereas neither decision support systems (DSSs), resistant cultivars in potato or cereal cultivations, nor alternative weed management have currently been applied. The dissemination of conclusions that were not evidence-based was also found.

Opportunities that could benefit IPM research in the future were identified. There was an overlap between calls so that some projects were built on multiple individual applications funded by one or both funding bodies. This emphasizes the need for more collaboration between the two funding bodies that could enable financing of larger projects and improve their outcomes. In addition, results from financed projects merit a broader audience and a long-term-availability. International, peer-reviewed publication of results should be encouraged to strengthen scientific quality and ensure that planning of research and results meets scientific standards. This would stimulate improvement of scientific quality of the research, and therefore support evidence-based implementation and advice to farmers. We further recommend that future research schemes focus more on integrated and innovative approaches to pest management that aim for a long-term reduction in dependency on plant protection products (PPP). This is emphasized by the results of projects showing the presence of resistant pest populations to currently used pesticides. There is particularly a need for integrated research studies targeting the complex of pests in a crop over a longer time period. The latter recommendation is also in line with the recently published national food strategy bill².

In conclusion, this report shows that, despite several challenges, considerable advances have been made in the field of IPM in Sweden, both in terms of research and implementation in practice. The necessity for improved quality of research to enable implementation of evidence-based solutions through a dissemination network and for long-term funding opportunities for coordinated collaborative efforts nationally and internationally were highlighted. The development and support of economically sound, alternative and integrated pest management strategies are particularly essential to enable successful adoption of IPM in the future.

² A National Food Strategy for Sweden - more jobs and sustainable growth throughout the country [original title: En livsmedelsstrategi för Sverige – fler jobb och hållbar tillväxt i hela landet] (Government action plan N2017/00647/KOM, 2017).

Abbreviations

BCN: Beet cyst nematode (*Heterodera schachtii*)
Bioforsk: Norsk institutt for skog og landskap (Norwegian Institute of Forestry and Landscape, now NIBIO)
BioSoM: Biological Soil Mapping (thematic research programme, SLU)
C-IPM: Coordinated Integrated Pest Management in Europe (European ERA-NET project)
DON: Deoxynivalenol (mycotoxin)
DSS: Decision Support System
EFSA: European Food Safety Authority
EQ: Environmental impact quotient
EU: European Union
Formas: Forskningsrådet för miljö, areella näringar och samhällsbyggande (The Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning)
GU: Göteborgs universitet (University of Gothenburg)
GPS: Global Positioning System
HS: Hushållningssällskapet (The Rural Economy and Agricultural Societies)
IIRB: International Institute for Beet Research
JTI: Institutet för jordbruks- och miljöteknik (Swedish Institute of Agricultural and Environmental Engineering), earlier Jordbrukstekniska institutet, now part of RISE,
Kemil: Kemikalieinspektionen (Swedish Chemicals Agency)
LD: Lethal Dose
LRF: Lantbrukarnas riksförbund (The Federation of Swedish Farmers)
LTU: Lunds tekniska högskola (Faculty of Engineering, Lund University)
MISTRA: Stiftelsen för miljöstrategisk forskning (Swedish Foundation for Strategic Environmental Research)
MRL: Maximum Residue Levels
NBR: Nordic Beet Research Institute
NIBIO: Norsk institutt for bioøkonomi (Norwegian Institute of Bioeconomy Research, earlier Bioforsk and Nifl)
Nifl: Norsk institutt for landbruksøkonomisk forskning (Norwegian Institute of Agricultural Economy Research, now NIBIO)
OiB: Odling i balans
ÖKS: EU-interregional programme Öresund-Kattegatt-Skagerrak (Denmark/Sweden/Norway)
PPA: Växtskyddscentralen (Swedish Plant Protection Agency)
PPP: Plant Protection Product
PVO: Planteværn Online (Crop protection online), a Danish DSS for weed management
R&D: Research and Development
RISE: Research Institutes of Sweden (earlier SP, Swedish ICT Research AB and Inventia AB)
SCB: Statistiska centralbyrån (Statistics Sweden)
SECV: Standard Error of Cross Validation
SLU: Sverige lantbruksuniversitet (Swedish University of Agricultural Sciences)
SMHI: Sveriges meteorologiska och hydrologiska institut (Swedish meteorological and hydrological institute)
SP: Sveriges tekniska forskningsinstitut (Technical Research Institute of Sweden), now part of RISE
SSNC: Naturskyddsföreningen (The Swedish Society for Nature Conservation)
STB: Septoria tritici blotch disease (caused by *Zymoseptoria* [other name: *Septoria*] *tritici* in wheat)

Glossary

Biopesticide: a biotechnical organism (in other words, a living organism) that has been produced specially to prevent or counteract damage caused by animals, plants, or microorganisms.

Biostimulant: a substance or microorganism applied to plants with the aim to enhance nutrition efficiency, stress tolerance and/or crop quality traits, regardless of its nutrients content.

Cisgenesis: a genetic modification of plant with cisgenes only, i.e., a natural gene coding for an (agricultural) trait, from the crop plant itself or from a sexually compatible donor plant that can be used in conventional breeding.

Crop rotation: the succession of different crops on the same land over a given period.

Economic threshold: pest population level or extent of crop damage at which the value of the crop destroyed exceeds the cost of controlling the pest.

Forecasting model: model in which different factors, such as weather data and pest pressure, are weighed together to predict if and when the organism will cause damage. This may also include advice on control measures.

Key to adapt pesticide dose: means for adapting the dosage of the pesticide. It shows how various factors, such as soil type and pest pressure, affect the dose of plant protection products need to be used.

Non-chemical methods: physical, mechanical, thermal, or biological methods to control pests and weeds or preventive methods that are an alternative to the use of chemical pesticides.

Pests: fungi, insects, virus or other organism that cause economic damage (qualitative or quantitative) to a crop.

Pesticide: collective term for plant protection products and biocides designating a product that is intended to prevent or counteract damage caused by animals, plants, or microorganisms.

Phytosanitary measures: measures taken to protect plants against harmful organisms or prevent action of such organisms in influencing the life processes of plants, to preserve plant durability.

Plant Protection Product: product used in agriculture, forestry, and horticulture to protect plants against harmful organisms (Regulation (EC) No 1107/2009 concerning the placing of plant protection products on the market).

Project: Individual study or compilation of multiple studies (i.e., granted through multiple applications) that addresses a unique research target and is carried out by the same research group.

Resistance: Ability to withstand a destructive agent or condition such as a chemical compound, a disease agent, or an environmental stressor due to selection pressure.

Resistance to pesticide: change in the sensitivity of a pest population to a pesticide, resulting in the failure of a correct application of the pesticide to control the pest.

Resistant variety (breeding): variety preventing (or limiting) the establishment of the targeted pathogen.

Risk assessment: Evaluation of risk (e.g., pest pressure, pest establishment in new regions). Can also be a variant of forecasting models.

Study: Successfully granted application.

Synthetic pesticides: Produced by synthesis instead of being isolated from a natural source, in which case they are referred to organic-, inorganic-, or biopesticides.

Teratogen: Agent or factor which causes malformation of an embryo.

Tolerance (pesticide): natural tendency for part of a population (e.g., life stage, size) to withstand pesticides. Contrarily to resistance, this is not a result of selection pressure. Can also be referred to as natural resistance rather than true insecticide resistance.

Tolerant variety (breeding): variety able to develop, continue growing and produce well despite the pathogens' presence.

Introduction

The directive 2009/128/EC of 21 October 2009 from the European Union (EU) establishes: a framework to achieve a sustainable use of pesticides by reducing the risks and impacts of pesticide use on human health and the environment and promoting the use of integrated pest management and of alternative approaches or techniques such as non-chemical alternatives to pesticides (Art. 1).

It defines:

integrated pest management (IPM) [as the] careful consideration of all available plant protection methods and subsequent integration of appropriate measures that discourage the development of populations of harmful organisms and keep the use of plant protection products (PPPs) and other forms of intervention to levels that are economically and ecologically justified and reduce or minimise risks to human health and the environment. IPM emphasises the growth of a healthy crop with the least possible disruption to agro-ecosystems and encourages natural pest control mechanisms (Art. 3.6).

This directive has implication for all:

Member States [that] shall adopt National Action Plans to set up their quantitative objectives, targets, measures and timetables to reduce risks and impacts of pesticide use on human health and the environment and to encourage the development and introduction of IPM and of alternative approaches or techniques in order to reduce dependency on the use of pesticides. These targets may cover different areas of concern, for example worker protection, protection of the environment, residues, use of specific techniques or use in specific crops (Art. 4.1).

The general principles of IPM are described in the Annex III of the directive (Appendix 1).

As a result, the Swedish Board of Agriculture (Jordbruksverket) published national rules and general guidance based on the annex III to the implementation of IPM³:

- Preventive measures should be implemented (§ 2)
- Pests should be monitored (§ 3)
- PPPs should be used at an optimal dose, non-chemical methods favoured, and strategies preventing resistance implemented. PPPs should have the highest specificity and lowest impact on human health and the environment as possible (§ 4)
- Effect of control measures should be assessed (§ 6)

The adoption of IPM is moreover part of the Swedish National Action Plan for the sustainable use of PPPs for the period 2013–2017⁴.

To support the adoption of the EU-directive, governmental incentives were introduced to stimulate research and development (R&D) in the field of IPM. As such, the government, through The Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning (Formas), entrusted Stiftelsen Lantbruksforskning with this task. Stiftelsen Lantbruksforskning is an independent funding body supported annually by public and private funds within the agricultural sector that aims at financing research of high relevance for the agricultural sector and of high scientific quality. In addition, Stiftelsen Lantbruksforskning provides annual base-financing for the national field trials granted on a yearly basis. In parallel, Jordbruksverket receives, each year, public funds that are intended to promote

³ Regulations and general advice of the Swedish Board of Agriculture on integrated plant protection [original title: Statens jordbruksverks föreskrifter och allmänna råd om integrerat växtskydd] SJVFS 2014:42

⁴ Nationell handlingsplan för hållbar användning av växtskyddsmedel för perioden 2013–2017 (2013–06–19).

research required to reach the environmental goals fixed by the government. Several knowledge gaps preventing the adoption of IPM were identified by Jordbruksverket which were the basis of research calls with IPM focus launched by Jordbruksverket. This report presents an extensive analysis of IPM research financed by Stiftelsen Lantbruksforskning and Jordbruksverket during the period 2009–2014 aiming at making recommendations for future research initiatives in the field of IPM. It describes the calls launched (**I**), presents the bibliographic outputs of the projects and compiles their findings in the different cropping systems (**II**). Then, an in depth-analysis of the four major pest/crop systems targeted by research projects are studied, where the system is presented, and projects and outputs described in detail. Implementation of results is discussed based on interviews with researchers and advisors, and needs for future research are compiled (**III**). The general assessments of this synthesis report are finally presented and general recommendations given (**IV**). This synthesis report is intended to serve as a basis for the development of future research calls and research programmes targeting IPM in Sweden.

I. IPM Research Calls and Studies Funded (2009–2014)

1. Research calls launched by Stiftelsen Lantbruksforskning and Jordbruksverket

1.1. Special IPM calls

Since 2009 Stiftelsen Lantbruksforskning, alone or together with Formas, has launched several calls with openings for IPM research proposals. Jordbruksverket has also launched IPM calls in this period. Some of these calls were special calls encouraging R&D, method testing and development, or, for Jordbruksverket, compilation of existing knowledge. Other calls focused on organic farming or genetic resistance in plant breeding. In addition to the special calls on IPM, several studies also originated from the open calls launched by Stiftelsen Lantbruksforskning and Jordbruksverket.

1.1.1. Special calls launched by Stiftelsen Lantbruksforskning in collaboration with Formas

In 2009 Stiftelsen Lantbruksforskning launched a special call with IPM focus that ran on an annual basis until 2013, with a total budget of 65.6 MSEK that financed 52 studies. These calls focused on both R&D studies within the R&D programmes in plant production⁵ and field trials including method development.

Priority was given to research studies with an expected practical application within five to ten years and to development studies with a priority given for plant protection studies that could result in a practical application in Sweden within three to five years. A major focus was given to major economic crops, and IPM research in horticultural crops was funded for up to 1 MSEK/year.

The main priority was given to studies developing alternative control methods (biological, mechanical, or chemical) that could result (1) in new control methods with reduced risks for the environment and health, and could be combined with mechanical or chemical methods; (2) in an inventory of the biological and economic potential for alternative control methods.

The priorities for development studies were (1) control strategies for economically important pests with minimal risk for developing resistance to pesticides⁶ and (2) decision support tools for chemical control of key pests and weeds. Other priority areas were the development of (3) databases for inventory variety tolerance as well as (4) dose-response curves for pesticides in relation to crop development stage, weed development, pressure level, as well as abiotic factors.

In 2009 Stiftelsen Lantbruksforskning launched a special call for 'Plant Breeding' in collaboration with Formas amounting to 24 MSEK. A total of six studies were granted, three of which were financed by Stiftelsen Lantbruksforskning. Although all of them did not fall within the IPM definition, one study funded by Stiftelsen Lantbruksforskning focused on breeding for resistance, which is a major aspect of IPM and is therefore included in this synthesis. This study is also included in the studies financed through the special IPM call.

In collaboration with Formas, Stiftelsen Lantbruksforskning launched a special call for organic production and consumption in 2013. The proposals were classified and evaluated within the appropriate focus area of the R&D programmes⁷. A total of six studies were

⁵ 'Plant production' regroups the following R&D programmes: Crop production, Potato, Sugar, Horticultural crops, Grassland and forage crops, and Plant breeding

⁶ *In italic*: in calls launched after 2010

⁷ Plant production, Field trials, as well as Bioenergy, Entrepreneurship, Meat, Milk, and Poultry

funded, one of which focused on breeding for resistance in organic farming, which is an important aspect of IPM.

1.1.2. Special calls launched by Jordbruksverket

Jordbruksverket launched a special IPM call⁸ for trials and development in 2011 (for period 2012–2014) with a budget of 3.5 MSEK. The aim of the call was to support the implementation of the EU-directive on sustainable use of pesticide with a practical application of research results within three years, with studies addressing knowledge gaps identified by Jordbruksverket. Priorities were given to (1) the compilation of existing knowledge, (2) the compilation and evaluation of existing preventive measures, with a focus on methods used in (long-term) field trials, (3) the validation or development of methods to monitor pests and adapt control methods, (4) the prevention of resistance development, (5) the development of biological, physical and other non-chemical methods that can replace or complement chemical methods, and (6) other topics such as the development of web-based support of IPM initiatives, the use of demonstration farms in the dissemination of applied IPM practices, or the compilation of existing methods to minimize leakage of pesticides from greenhouses. Some of these priorities were very detailed, with the aim to fill specific knowledge gaps identified by Jordbruksverket. **A total of 12 studies were granted for a total budget of 3.76 MSEK.**

1.2. IPM in open calls

In addition to the special calls, research proposals with IPM perspectives were received in the open calls from Stiftelsen Lantbruksforskning within the ordinary R&D programme areas related to plant production since 2009. Each R&D programme described specific examples within each defined priority. IPM focus in plant production studies became obligatory in 2014 and IPM focus was encouraged within Stiftelsen Lantbruksforskning's research priorities, i.e., applied research, concept development and proof of concept (Figure 1). **A total of 16 applications were approved in this way during the period 2009–2014.** One study granted in the R&D programme 'bioenergy' was additionally selected for its focus on weed management.

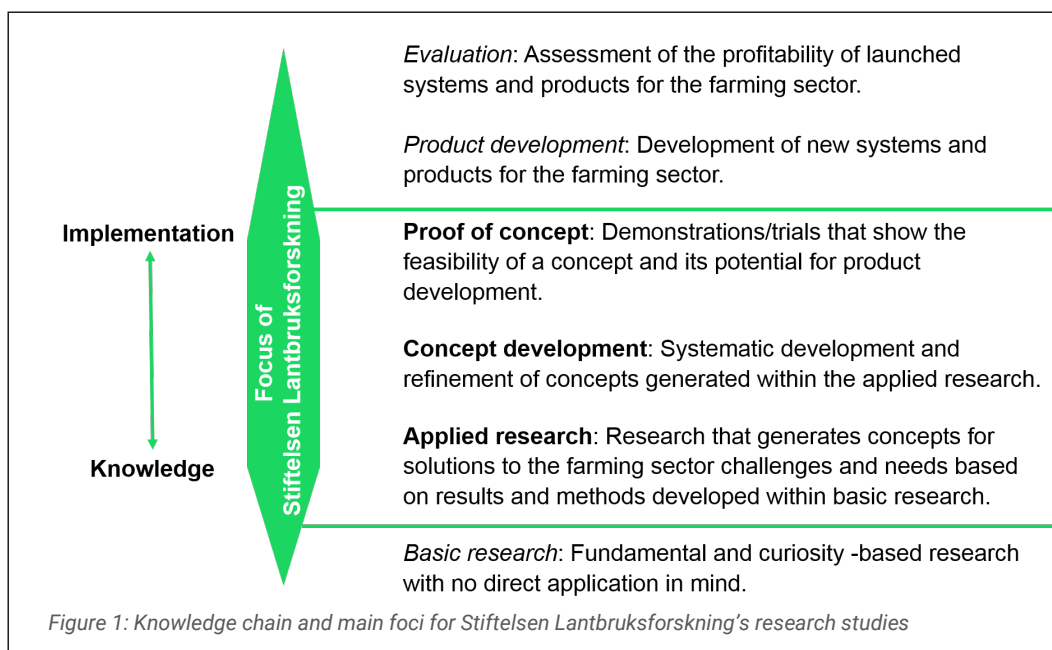
Twenty-five studies with IPM focus were granted by Jordbruksverket through the general calls in the trial and development programme 'A non-toxic environment'⁹ during the period 2011 and 2013. The studies were granted for up to three years. Multi-year projects were financed one year at the time upon submission of a new application each year, the initial budget being reserved for the entire period initially applied for. In 2013, only a limited sum was left after attribution of the reserved budget for ongoing projects, so that the call targeted projects financed for a maximum of three months.

Since the calls launched in 2011, priorities were given to developing biological, physical, and other non-chemical methods to replace or complement chemical methods, as well as more areas where needs were identified:

- **In 2011 (for studies starting in 2012):** validate or develop methods to monitor pests and adapt control methods; prevent the development of pest resistance
- **In 2013 (for studies running in Sept–Dec 2013):** estimate the cost of preventive and alternative measures in crop protection; develop more efficient spraying techniques
- **In 2013 (for studies starting in 2014):** reduce pest pressure in the crop rotation with focus on winter and spring oilseed rape.

⁸ Apply for projects for integrated plant protection projects [original title: Sök bidrag för projekt om integrerat växtskydd] (Jordbruksverket, 2011).

⁹ Original name: Försök och Utveckling inom Miljökvalitetsmålet Giftfri miljö.



1.3. Contracted studies by Jordbruksverket

In addition to their open calls, Jordbruksverket can directly finance a specific study they identify as needed based on identified knowledge gaps. A direct contract is then directly established with a researcher, advisor, or institution. A call for proposals addressed to several institutions can also be done, resulting in a contract signed with one of the interested institutions. **Five studies included in this synthesis were contracted by Jordbruksverket for a budget of 1.31 MSEK.**

1.4. Call requirements and funding selection procedures

1.4.1. Study requirements

The requirements of Stiftelsen Lantbruksforskning varied according to the R&D programme to which the study applied. Research of high relevance for the agricultural sector and of high scientific quality is targeted by Stiftelsen Lantbruksforskning. A reference group with representation from industry, advisory services and researchers was required for applications within the R&D programme 'Potato' in 2009, and a 'suitable' reference group was required in the programme for field trials and method development between 2009 and 2012. In addition, co-financing with the industry could be requested by Stiftelsen Lantbruksforskning, such as within the R&D programme 'Potato' in 2009 when a call for a 5 MSEK project was launched with obligatory co-financing from the industry. Co-financing from the industry was further requested within the R&D programme 'Plant breeding'. In addition, requirements regarding the education of graduate students can be made by Stiftelsen Lantbruksforskning such as in the case of the special call 'Plant Breeding'.

Both Jordbruksverket and Stiftelsen Lantbruksforskning have required the publication of a final report, due respectively one and six months after study completion. A short report describing the progress of a study is further required each year for multi-year studies. In the case of multi-year studies financed by Jordbruksverket, this progress report is included with the new application sent each year.

Communication to both stakeholders via national fact-press and the scientific community via peer-reviewed scientific articles in international journals has been encouraged by Stiftelsen Lantbruksforskning, and is mentioned in its strategic plan since 2012. Stiftelsen

Lantbruksforskning requires a description of the planned communication channels for the results in all applications for funding. An updated list of publication and alternative means of result dissemination is additionally required in the final report. Peer-reviewed publications are encouraged by Jordbruksverket since 2012. Planned additional publication is generally mentioned in Jordbruksverket application, but rarely in the final report. The requirements of the contracted studies in terms of publication are specific to each contracted study. A final report is generally required. An external review of the statistics used in the analysis can also be suggested wherever applicable.

1.4.2. Funding selection procedure

The selection of studies differs between the two funding bodies. Stiftelsen Lantbruksforskning relies on an external evaluation committee, which until 2014 was composed of both external stakeholders and academic reviewers who assessed the relevance for the agricultural sector and the scientific value of all applications¹⁰. At Jordbruksverket the selection of granted studies is internally performed following a point-based evaluation. Each application is reviewed by a member of the staff of the research unit and by a plant protection expert in the area targeted by the application.

2. Granted studies and result dissemination channels

2.1. Selection of studies included in the report

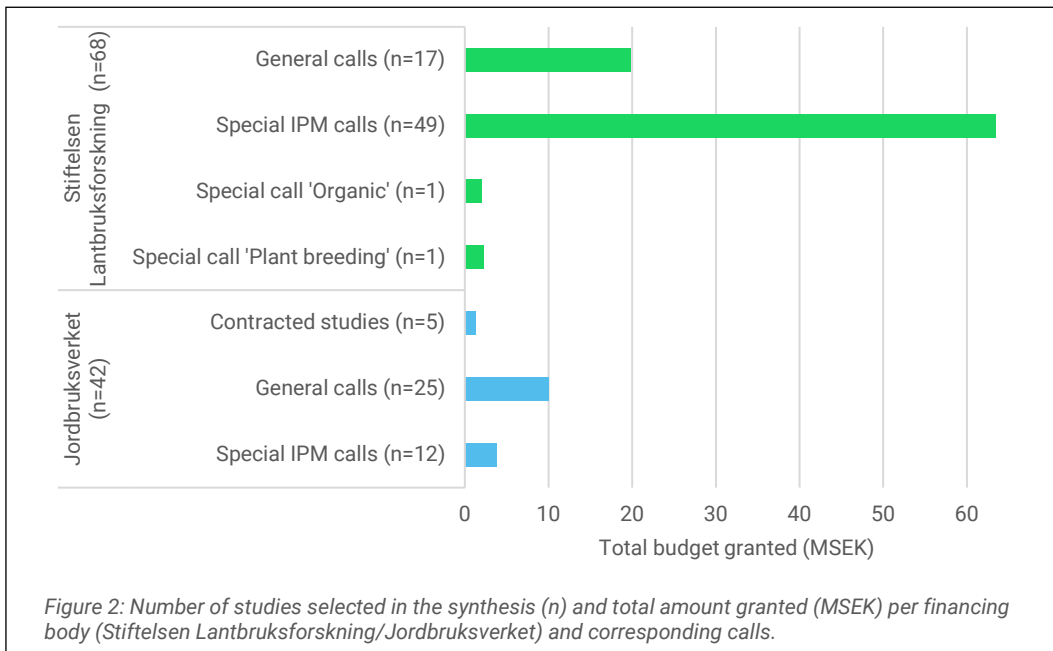
2.1.1. Selection criteria

The studies included in the present synthesis report are:

- all terminated studies financed through the special "IPM" calls from Stiftelsen Lantbruksforskning: **49 studies** out of 52 granted (one aborted, one still ongoing, and one affiliated to the special call 'Plant breeding' were not included)
- all studies financed through the special IPM calls from Jordbruksverket (period 2012–2014): **12 studies**
- all contracted studies by Jordbruksverket financed during 2009-2014: **five studies**
- all studies with IPM focus granted through the general Jordbruksverket calls in the period 2011–2014: **25 studies** (communicated by Jordbruksverket)
- all terminated studies financed by Stiftelsen Lantbruksforskning after 2009 that covered IPM aspects associated with the general (**17 studies**) and special calls 'Plant breeding' (**one study**) and 'Organic production and consumption' (**one study**) were selected.

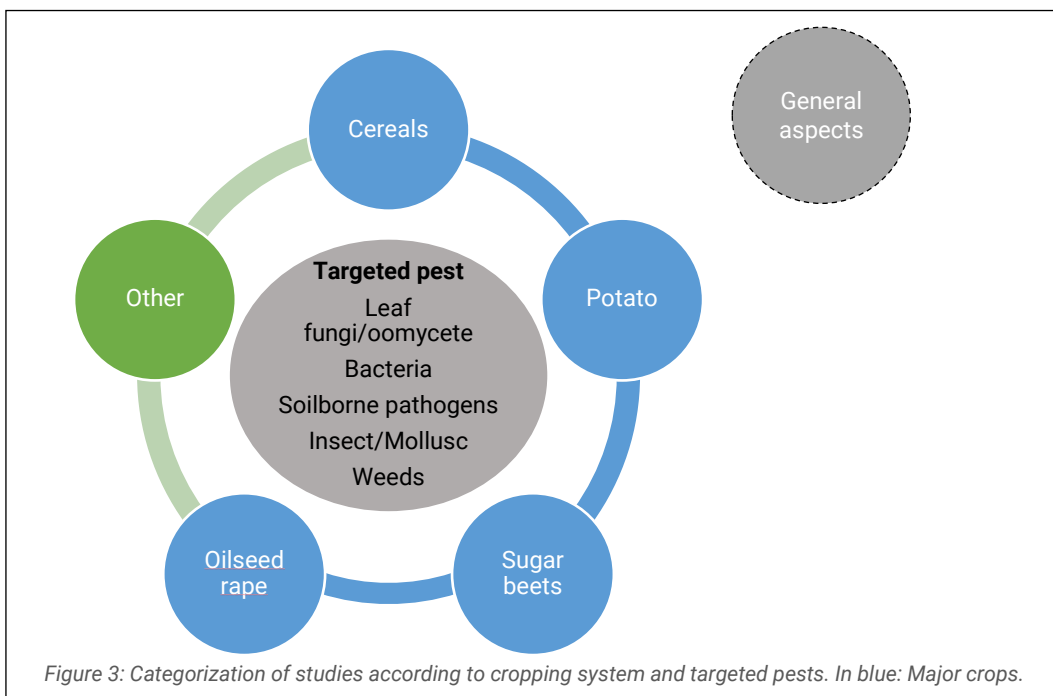
A total of 110 individual studies have been included in, and form the basis of, this synthesis report. The funding source and corresponding call are summarized in Figure 2. Additional studies funded by Jordbruksverket through the special call "Organic production" are not included in this report for practical reasons.

¹⁰ Since 2014 a two-step procedure has been implemented with the relevance for the agricultural sector assessed in the first and second step by external stakeholders and the scientific value assessed by external academic reviewers in the second step.



2.1.2. Categorization of studies

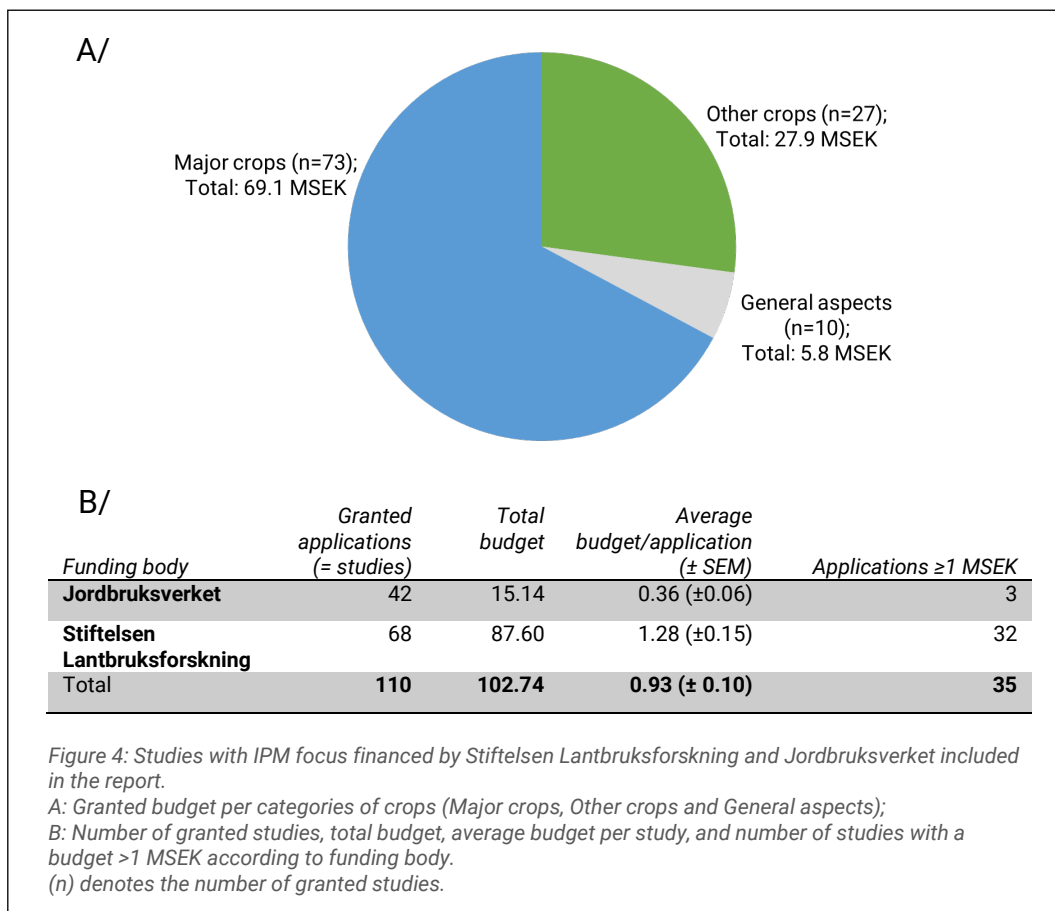
The selected studies (R&D studies as well as method and development studies) were analysed according to the studied cropping systems and targeted pests (Figure 3). Cereals, potato, sugar beets, and oilseed rape are the major economic crops grown in Sweden (hereafter, 'Major crops'). Some studies had a focus on some general aspects of IPM without a focus on a particular crop or system and are hereafter mentioned under 'General aspects'.



Additionally, the selected studies were characterized according to their major focus, following the national regulations for IPM implementation:

- **Prevention** which includes studies on pest biology (including resistance mechanisms), mapping, and the use and development of resistant varieties
- **Monitoring** which includes studies developing diagnostic tools and forecasting systems
- **Optimization of control**, which includes studies optimizing doses and application methods, defining economic thresholds, developing decision support systems (DSS), strategies to prevent the development of PPP resistance, and Alternative control methods (mechanical control, biological control, biopesticides)
- Efficacy of PPP used.

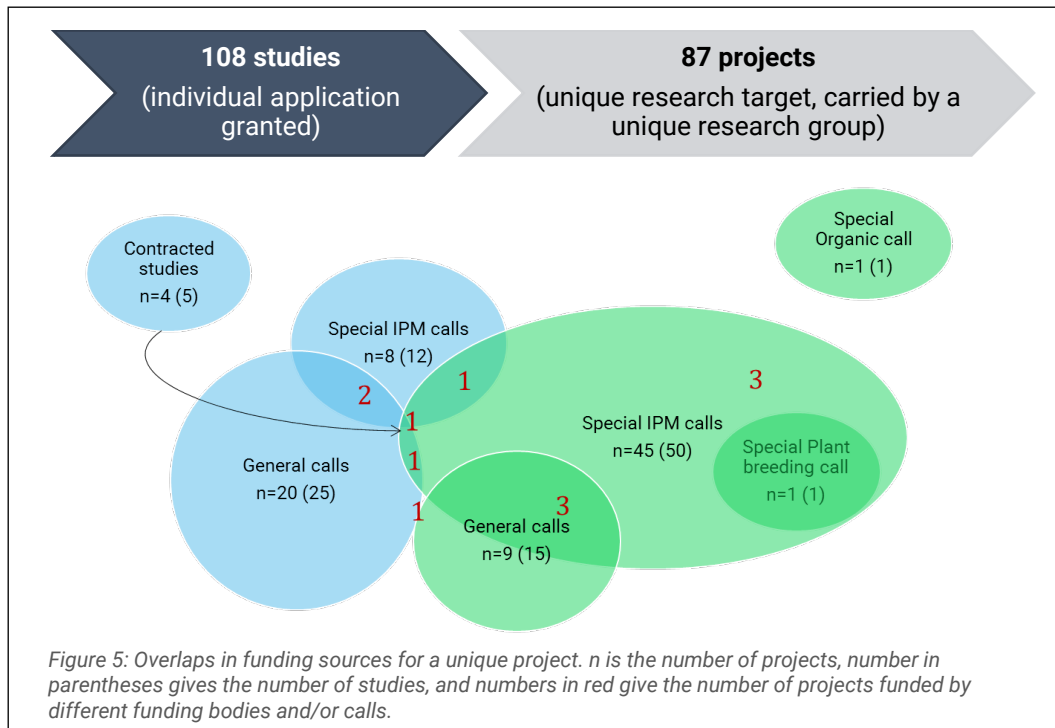
A majority of the 110 studies granted mainly focused on IPM in major crops (Figure 4). Two studies were excluded from further analyses as the IPM focus described in the application had not been investigated in the project.



From these studies, a total of **87 independent research projects** were identified that received funding through a single or multiple applications for the same research target and carried out by the same research group. These projects were associated to their main source of funding and assigned to a single identifier. Each project included an average of 1.2 studies (range: 1-4), with principal funding from Stiftelsen Lantbruksforskning (55 projects) or Jordbruksverket (32 projects). They had an average total budget of 1.5 MSEK (± 0.15) when the major funding source came from Stiftelsen Lantbruksforskning and 0.4 MSEK (± 0.08) when the major funding source came from Jordbruksverket. Some of the

projects have received additional funding from another funding body, which are not accounted for in the analysis for practical reasons.

There were overlaps between the different calls launched by Stiftelsen Lantbruksforskning and Jordbruksverket in the financing of a project (Figure 5). For example, nine studies granted by Jordbruksverket (19 %), for a total of 2.34 MSEK (15 % of the total research budget from Jordbruksverket included in this synthesis) have co-funded a larger project funded by Stiftelsen Lantbruksforskning (four studies) or funded a pilot study that lead to a larger study (three studies + two ongoing) funded by Stiftelsen Lantbruksforskning or Formas.



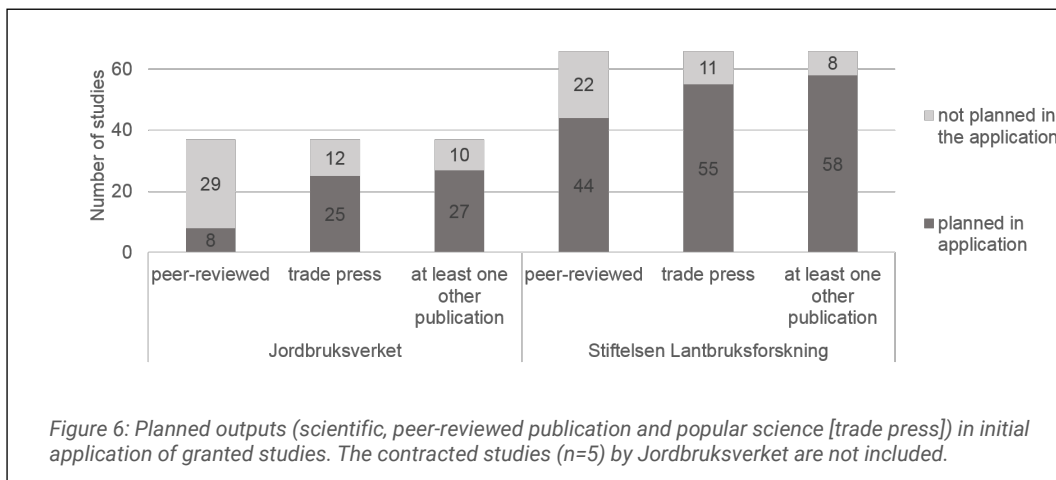
2.2. Target audience of the studies and communication of results

The target audience varies according to studies, which can preferentially target farmers, advisory services, those responsible for field trials, industry, policy makers and/or the broader scientific community. The target audience is generally described in the funding application, together with the channels envisaged to disseminate, in writing or orally, the outputs of the study. For the contracted studies by Jordbruksverket, the target audience was Jordbruksverket itself that aimed to use the results as a basis for decision making when developing IPM implementation in Sweden.

In addition to their target audience, these channels differ in their accessibility in the short- and long terms, the availability of the data, as well as the levels of inputs and quality assessment from peers before dissemination. Popular publications include all fact-sheets and articles in the trade press (printed/online). Whereas articles in the trade press may vary a lot in terms of content and accessibility, the fact-sheets generally describe the experiment carried out, the results and the conclusions of the project and are archived by the institution that carried the study and made available online. Peer-review publications (articles/books, theses) are the only type of publication providing objective quality insurance for the study. The process also provides valuable feedbacks from peers to the author for further

improvements. Characteristics of the different publication channels used to disseminate outputs of the research projects are summarized in Appendix 2.

Most studies had an initial plan to disseminate results through popular publications (Stiftelsen Lantbruksforskning: 83 %, Jordbruksverket: 60 %), most of them targeting farmers and advisory services. The final report, submitted for all studies upon completion (i.e., between 2009 and 2016), can also be used to disseminate the results of a study. Respectively 27 % and 12 % of studies funded by Jordbruksverket (excluding all contracted studies) and Stiftelsen Lantbruksforskning had as their only publication plan to publish the final report. Such a report generally describes the aims, methods and achievements of a study. In addition, publication in peer-reviewed journals was planned in most studies funded by Stiftelsen Lantbruksforskning (68 %), and to a lesser extent in Jordbruksverket studies (19 %) (Figure 6). One contracted study did not specifically require the publication of a final report, and none required additional dissemination of the study outputs.



A similar pattern is observed in the actual publications¹¹ of the research projects (Figure 7):

- The final report was the sole publication for 16 % (Stiftelsen Lantbruksforskning) and 50 % (Jordbruksverket) of funded projects. Final reports are found online for all Stiftelsen Lantbruksforskning projects in the online database¹² and for 72 % of the Jordbruksverket projects in various databases
- 49 % of Stiftelsen Lantbruksforskning and 16 % of Jordbruksverket funded projects included at least a peer-reviewed publication published or at the manuscript stage, with an average of 1.6 (range 1–5) publications per project and a total of 36 articles published (Table 1)
- 62 % (n=34) of Stiftelsen Lantbruksforskning and 25 % (n=8)¹⁰ of Jordbruksverket funded projects included at least a popular publication (archived fact-sheets, popular articles in printed/online fact-press). Fact-sheets were published for 9 % of the projects
- Some projects contributed to the education of graduate and undergraduate students
- One patent has been registered (Stiftelsen Lantbruksforskning-project).

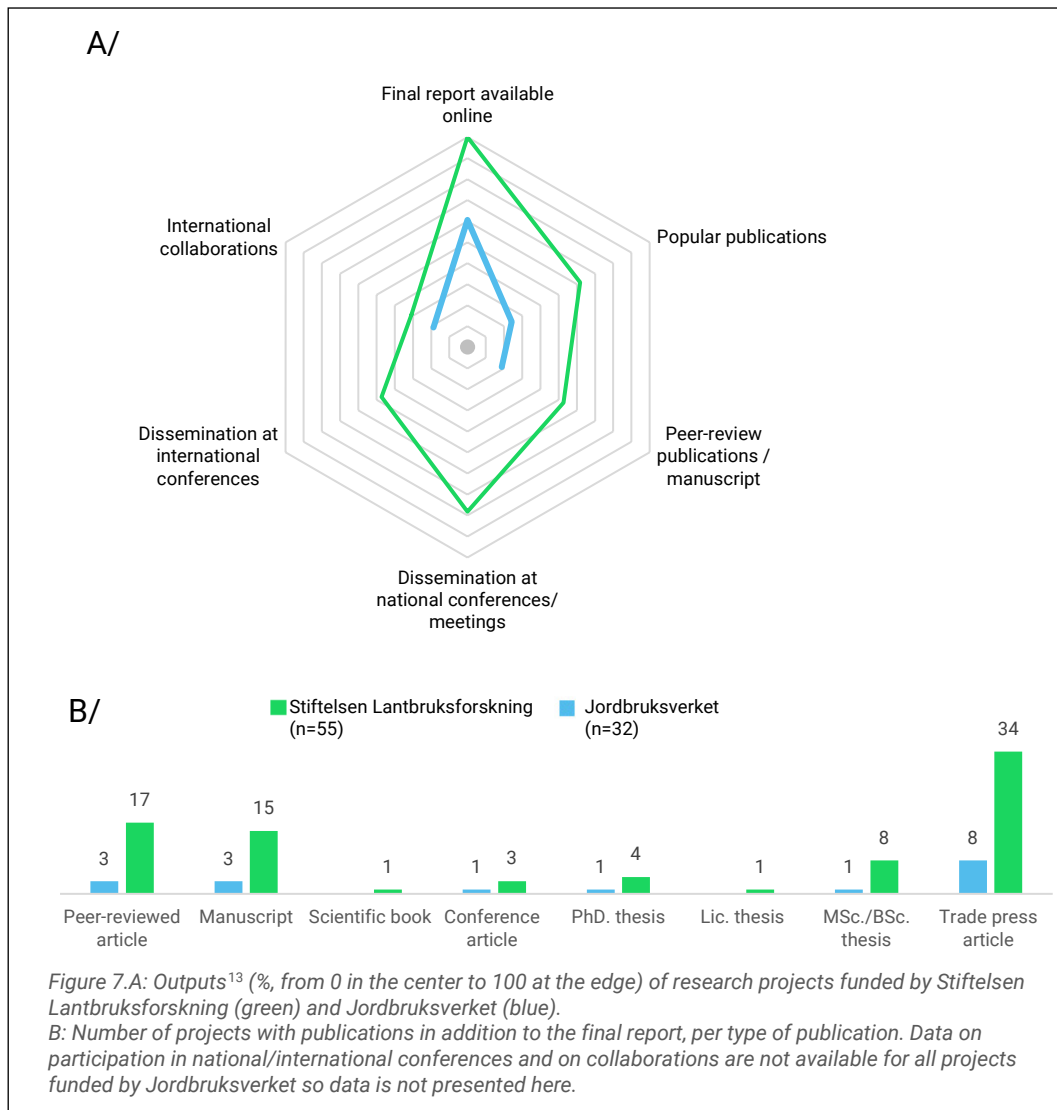
In addition, dissemination could be done orally through collaborations and through the participation to conferences nationally and/or internationally. Overall scientific publications of the 87 research projects are summarized in Table 1.

¹¹ The list of publications was extracted from the final reports and was updated via contact with the principal investigator of each study [November 2016–January 2017]. Numbers of popular publications might be underestimated for Jordbruksverket-funded projects as the publication list is not requested and is rarely included in the final reports from Jordbruksverket.

¹² <http://www.lantbruksforskning.se/projektbanken>

Table 1: Overview of the written published outputs of the 87 research projects included in this synthesis report.

	Type of Publication	Number
Academic publications	PhD thesis	4
	Licentiate thesis	1
	MSc/BSc thesis	15
Scientific publications	Peer-reviewed article	36
	Manuscript	25
	Conference article	8
	Book	1
Patent	Patent	1
Trade press articles	Online	14
	Printed	78



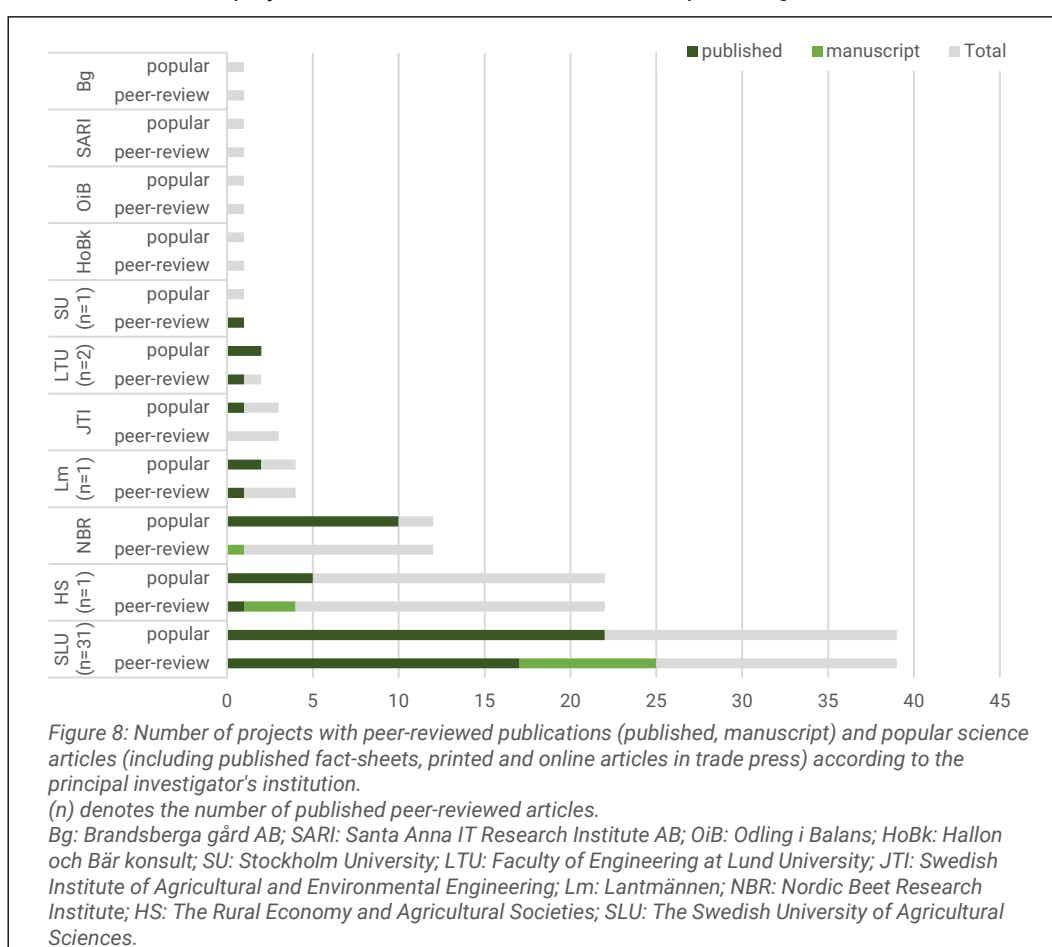
¹³ Projects with international collaborations were defined as projects that published at least one publication of any kind together with researchers from another country or that carried trials in different countries.

3. Outputs and project characteristics

3.1. Applicants

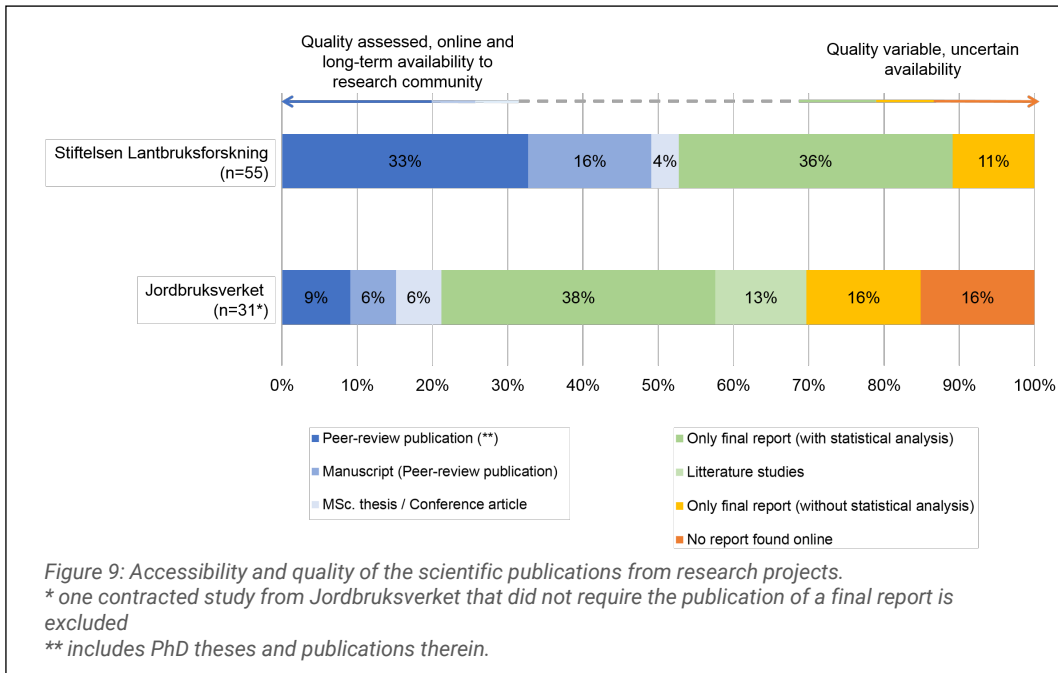
Applicants from SLU carried out the highest number of granted projects with 39 projects, followed by applicants from two applied agricultural organizations carrying research and providing advisory services (Hushållningssällskapet [HS]: 22 projects and Nordic Beet Research Institute [NBR]: 12 projects). Applicants from universities and advisory services collaborated as main and co-applicants in 27 % of the projects funded by Stiftelsen Lantbruksforskning (data not available for Jordbruksverket). Such collaborations reached 5.4 % between industry and universities, and 7.3 % between industry and advisory services.

The universities SLU, SU and LTU had the highest rates of publications in peer-reviewed journals (Figure 8), and all first authors of peer-reviewed publications of research results were to some extent affiliated with a university. NBR and SLU had the highest rates of dissemination of projects results in fact-sheets and in trade press in general.



Applicants with experience in international peer-reviewed publishing were the main applicant for 76 % of the studies, without distinction between funding bodies. Of the other 24 %, none have resulted in the publication of a peer-reviewed article, and results have been, if published elsewhere, exclusively disseminated in the trade press. Final reports including statistical analysis were more frequent when led by a principal investigator that held a PhD (38 %) compared with reports produced by a principal investigator that did not hold a PhD (18 %).

In addition, the final reports varied greatly in terms of information presented and scientific quality. Particularly, 42 % of the final reports of studies funded by Jordbruksverket (excluding literature studies) and 21 % of those funded by Stiftelsen Lantbruksforskning did not provide any results from statistical analyses. In the case that these final reports are the only publication of the project, the validity of the results must be considered questionable. The final report of 16 % (n=5) of Jordbruksverket studies cannot be found online (Figure 9) and none of the final reports from the contracted studies was available from Jordbruksverket's database (two are archived online elsewhere).



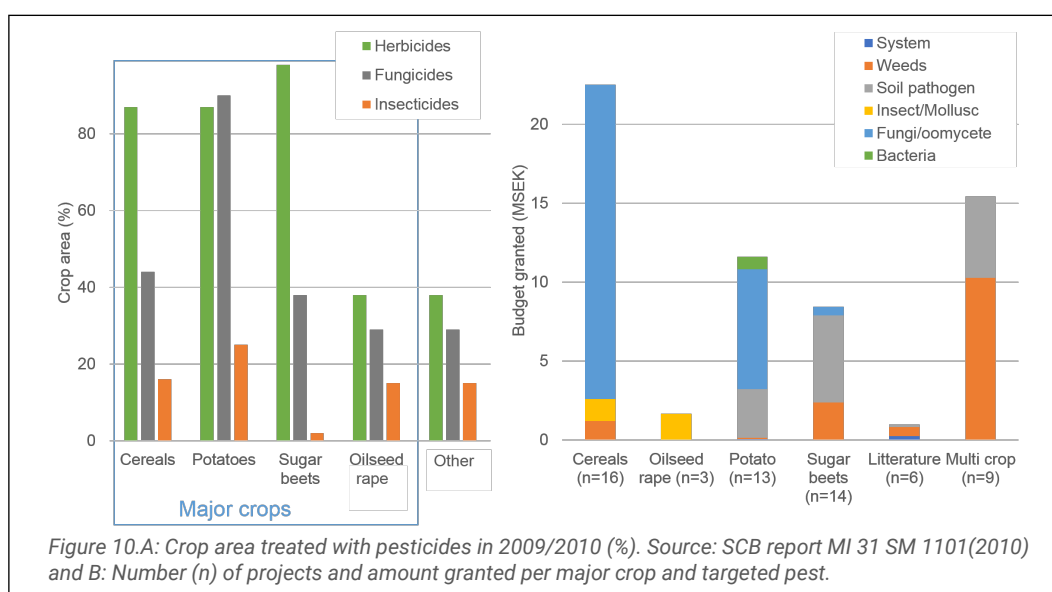
3.2. Budget

The budget of the granted studies varied greatly between studies and funding body, with a larger budget generally observed for studies funded by Stiftelsen Lantbruksforskning (Figure 4). The budget of projects with peer-review publications and/or a final report that included statistical analyses was higher than those that did not (with peer-review article: 1.72 MSEK ± 0.21, without: 0.65 MSEK ± 0.07; with statistical analysis in the final report: 1.09 MSEK ± 0.12, without: 0.52 MSEK ± 0.10). Nonetheless, there are examples of low-budget projects with publications in, among other channels, peer-review publications.

II. Granted Projects: Characterization, Scope, and Findings

1. Major crops

The focus of most research projects was IPM in major crops (cereals, potatoes, oilseed rape, and sugar beets). In these crops, pest management in conventional farming relies mostly, and in some cases heavily, on pesticide use (Figure 10A). A total of 60 projects¹⁴ were funded through 71 individual applications for a total of 60.64 MSEK. The amount granted and pest targeted by the granted projects are summarized in Figure 10B. All projects are listed in Appendix 3.



Fusarium Head Blight (FHB) in cereals, Potato late blight (*Phytophthora infestans*), beet cyst nematodes (*Heterodera schachtii*, BCN) in sugar beets and weed management in annual crops have received most of the research funding in the past years. A specific analysis of research findings, implementation and knowledge gaps is carried out for each system in section III.

1.1. Cereals

A total of 15 projects (A1–A15) set in cereal systems (wheat, oat, triticale or barley) are included in this synthesis report. In addition, four projects focused on different aspects of IPM in multiple cropping systems, including cereals. These projects are reviewed in more detail in the 'Mixed cropping' section (II.1.5). The mycotoxin-producing fungi *Fusarium* spp. has been the targeted pest in a majority of projects (13 projects), following by aphids (two projects). The research findings and their implementation for projects targeting FHB are further described and analysed in section III.1.

1.1.1. Fungi

Fusarium spp. (*F. langsethiae*, *F. graminearum*) has been the main target of the granted projects. Other targets alone or in combination were the fungal leaf spot diseases Septoria leaf blotch (caused by *Parastagonospora nodorum*) and Stagonospora nodorum blotch (or Septoria tritici blotch disease [STB] caused by *Zymoseptoria tritici*), the wheat stripe (yellow

¹⁴ One granted project (based on two applications) in the potato system did not deliver the IPM focus initially planned and is therefore excluded of the calculations.

rust disease (*Puccinia striiformis*), the yellow leaf spot disease (*Pyrenophora tritici-repentis*), and the eyespot disease (*Oculimacula yallundae*).

The aim of most projects was to improve/develop breeding programmes and testing of variety resistance. In addition, three multi-year projects investigated risk assessments for disease pressure, forecasting models, and cultural practices that minimize pest pressure in current and future cropping systems in Sweden, respectively. The source of disease spread and the epidemiology of wheat stripe (yellow) rust disease were each investigated in one project.

Research findings from these projects are summarized in Box 1.

Box 1: Main findings of IPM projects targeting fungi in cereal crops

Prevention

- **Biology**
 - The inoculum from wheat stripe (yellow) rust disease (*Puccinia striiformis*) does not result from sexual reproduction. Barberry (*Berberis* spp.), which is an alternative host commonly found in Sweden, does therefore not present an additional risk of propagation (project **A12**, Sjöholm et al. 2015).
 - Genetic populations of *P. striiformis* differ between cereals (spring wheat and both winter wheat and triticale) (project **A12**, Nilsson 2016).
 - Seeds contaminated with *F. graminearum* can introduce the pathogen to new areas (project **A11**, Persson et al. 2014).
 - A high genetic diversity of *Zymoseptoria tritici* causing the wheat STB disease is found in Sweden. Sexual reproduction occurs which increases the risk for virulent strains and development of resistance to fungicide. Commonly used PCR-primers are not adapted to Swedish conditions so that new primers developed for Swedish strains are needed to monitor Swedish populations (project **A7**, final report).
- **Risk assessment**
 - Importance of preceding crop and tillage in *Fusarium* management (projects **A8–A9**, Leplat et al. 2013, in Abid 2012; Leplat 2013).
- **Resistant variety**
 - Identification of genetic markers to be used to improve breeding for *Fusarium* resistance in barley (project **A1**, final report).
 - Isolation of mutant lines with increased *Fusarium* resistance, and identification of proteins involved in the resistance mechanisms in oats (project **A2**, final report).
 - Establishment of field trials to test variety resistance properties and study of best practices and their improvement to grade cereal diseases (projects **A3, A5, A6**, final reports).
 - (Partial) development of Loop-Mediated Isothermal Amplification PCR methods to detect *F. langsethiae* (project **A4**, final report).
 - No indication was found that attacks of STB differ between wheat varieties or locations in Sweden (project **A7**, final report).
 - Cost consideration (of e.g., fertilization, fungicide treatments) might need to be taken when using resistant varieties (project **N1**, final report). Further analyses would be needed to confirm these trends.

Monitoring

- **Forecasting**
 - (Partial) development of a forecasting model for *Fusarium* and DON in oats in Sweden (project **A10**, Persson et al. 2017).

- Development of methods to use spore traps for the detection of fungal diseases in cereals (project **A15**, *final report*).

Optimization of control

- **Alternative control**
- Importance of preceding crop and tillage in *Fusarium* management (projects **A8-A9**, Leplat et al. 2013, in Abid 2012; Leplat 2013).

1.1.2. Aphids (and virus)

Three granted projects targeted cereal aphids (*Rhopalosiphum padi*, *Sitobion avenae* and *Metopolophium dirhodum*), the vectors of barley yellow dwarf virus (BYDV) which causes damage in cereals, and particularly in winter wheat. They aimed at developing a risk assessment (**A13**), or at investigating the use of variety mixtures to reduce aphid pressure (**A14**). The latter project was a pilot study, which showed encouraging results and received further funding to scale up the project. The potential of vitamin B1 (thiamine) as a seed coating or solution to reduce aphid pressure was investigated in different crops, including cereals (**M1**). Another project (**N1**) investigated the cost of prevention in plant protection, and had as a case study delayed sowing in winter wheat to prevent aphid (and virus) damage. Main findings of projects targeting insects in cereal crops are shown in Box 2.

Box 2: Main findings of IPM projects targeting insects in cereal crops

Prevention

- **Biology**
- The cultivation of a mixture of barley varieties shows promising results in reducing aphid pressure (project **A14**, *final report*).
- **Preventive methods: cost consideration**
- The economic return of delayed sowing to prevent aphid damage seems to vary according to management options such as variation in seedling density, herbicide/insecticide/fungicide use (project **N1**, *final report*). Upscaling the study and further analyses would be needed to draw firm conclusions.

Monitoring

- **Forecasting**
- The presence of winged aphids is correlated with the presence of barley yellow dwarf virus in winter cereals (project **A13**, Sigvald 2012). A risk assessment for pesticide control could therefore be based on the presence of vectors (aphids, e.g., in suction traps).

Optimization of control

- **Alternative control**
- Thiamine used as seed coating and solution shows potential for reducing aphid population growth in barley and peas (project **M1**, Hamada and Jonsson 2013). The project has received additional funding¹⁵ to test the effect of thiamine in field conditions (L. Jonsson, personal communication).

¹⁵ Lantmännen project 20120021: Reinforcement of plant's resilience to reduce aphid infestation (funded in 2012)

1.2. Oilseed rape

A total of two projects (**B1**, **B2**) targeting grey field slug and flea beetle management in oilseed rape systems are included in this synthesis. One other project (**M2b**) investigated the suitability of biopesticides available in foreign markets. In yet one other project (**E1a/b/d**), the development of detection methods for soilborne fungi in different systems, including oilseed rape, was in focus. These projects are reviewed in more detail in their respective sections.

1.2.1. Slugs

Project **B1** had as its main focus the monitoring of grey field slug (*Deroceras reticulatum*) in oilseed rape. The aim of the project was to develop a risk assessment based on a method used in the UK, and to develop methods to minimize the risk of slug attacks at an early crop stage. The main finding of the project is the determination of slug population threshold in the preceding crop (one slug/trap/day), whereas the results showed no evidence of correlation between preceding crop, tillage, and sowing method on slug pressure (project **B1**, final reports).

1.2.2. Flea beetles

Project **B2** had as main focus the resistance status of flea beetles (*Phyllotreta* spp.) to insecticides (both seed and foliar treatments). The main finding of this project was the lack of efficacy of the only insecticide commercialized in Sweden for seed treatment (neonicotinoid, active ingredient: imidacloprid), and discussed the potential mechanisms involved. The results also show variation in the efficacy of foliar treatment, highlighting the risk of resistance development (project **B2**, Ekbom 2011, Ekbom and Müller 2011). This project provided evidence that the only insecticide (imidacloprid) then registered in Sweden for coating the seed of spring oilseed rape against flea beetles is not efficient in protecting the plant. Results further suggest that flea beetles might be developing resistance to foliar insecticides, calling for a reduction in the use of foliar spray (Ekbom 2011, Ekbom and Müller 2011).

1.3. Potatoes

Thirteen projects dealt with IPM in potato systems. The prevention and optimization of fungi and oomycete control, and particularly of *Phytophthora infestans*, were investigated in ten of these projects. One of these projects (**N1**) focused on the cost of prevention in plant protection in different cropping systems, including potato. Bacteria were the target of two research projects. One pilot project (**C10**) aimed at defining needs for future research for sustainable potato production. One project (**C4**) did not investigate the IPM focus which was part of the application (namely the 'focus on the capacity of the preceding crop to suppress diseases in the following potato crop') and is therefore not further discussed in this report. One other project (**A15**) initially aimed at developing methods to detect fungi/ oomycetes in agricultural fields, including potato fields, instead focused research on the cereal system and is therefore reviewed earlier (see II.1.1.1). Description of the research findings and their implementation of projects targeting *P. infestans* are further described and analysed in section III.2.

1.3.1. Fungi/oomycete

The oomycete/fungi targeted by the research projects are mainly late blight (*P. infestans*) and early blight (*Alternaria solani*). The aims of the projects were to develop resistant potato varieties (**C1**), to identify and develop diagnostic tools for leaf fungi for practitioners (**C2**), study the transmission process of *P. infestans* (**C3**), develop control thresholds and alternative fungal control methods (**C5**), develop the potential of commercial DSS (**C11**, **C12**) and of open weather data as inputs to DSS (**C12**). The study of the economic viability of potato late blight and brown rot control (**C6**), and of the resistance status of early blight to fungicides (**C7**) were the focus of two other projects. In another project (**M2b**), the suitability of biopesticides available on foreign markets against, among others, *Rhizoctonia solani* in potato was investigated. The main findings of these projects are shown in Box 3.

Box 3: Main findings of IPM projects targeting fungi/oomycete in potato crops

Prevention

- **Biology**
 - Development and online publication of a diagnostic tool for fungal disease based on leaf pictures and a questionnaire (available online¹⁶, project **C2**, *final report*). The interface is not user-friendly and would require additional development. So far, no follow-up project has been communicated regarding further development.
 - Identification of oospores as a potential source of inoculum to seed tubers for the epidemic of late blight (project **C3**, Sjöholm 2012, Sjöholm and Andersson manuscript).
- **Resistance**
 - Development of a new crossing methodology that improves the number of crossed and tested seeds (project **C1**, Eriksson et al. 2016).
 - Development and publication of new molecular markers for late blight resistance of the potato breeding clone SW93-1015 (project **C1**, Lenman et al. 2016). The project received additional funding in 2015¹⁷.
 - Premium price for resistant varieties might not be covered by the cost reduction generated by a decrease in fungicide use. Yield increase would then be needed so that farmers can achieve similar incomes. This study would need additional analyses to support these predictions (project **N1**, *final report*).

Optimization of control

- **Alternative control**
 - Identification of potassium phosphites as a potential player in plant defence against potato late blight in combination with reduced dosages of traditional fungicides (project **C5**, Liljeroth et al. 2016a, 2016b).
 - Potential improvement of profitability with a reduction of the amount of fungicides (project **C6**, Wiik et al. manuscript).
 - Widespread resistance of *Alternaria solani* to strobilurin fungicides (Qols) in Sweden (project **C7**, Odilbekov et al. 2016; Liljeroth 2016).
 - The use of bacteria mixture as a biopesticide against *Rhizoctonia solani* could not be assessed for technical reasons (project **M2b**, *final report*). Currently available as growth stimulator, the suitability of the product was discussed as it requires the users to self-grow the bacteria mixture and spray it on the crop. The risk of contamination by microorganisms and potential health hazard that could result from it were discussed, so that the use of the product is not recommended.

1.3.2. Bacteria

The management of the blackleg-causing bacteria was the focus of two research projects. The aims of these projects were to identify and map the species causing infection (**C8**) or to test alternative control methods (**C9**). Their main findings are shown in Box 4.

¹⁶ <http://alternariakollen.hushallningssallskapet.se>

¹⁷ Stiftelsen Lantbruksforskning project O-15-20-557: Development of late blight resistant ware potato varieties for most parts of Sweden [original title: Framtagning av bladmögelsresistenta matpotatisorter för stora delar av Sverige] (1.9 MSEK, E. Andreasson, ongoing)

The results of this project have been communicated through national channels. Project **C8** was part of a European collaboration (EUPHRESKO project for the control of blackleg throughout Europe) and the results are also published in their final report¹⁸.

Box 4: Main findings of IPM projects targeting bacteria in potato crops

Prevention

- **Biology**
 - Identification of the bacteria species responsible for latent infections of blackleg in Sweden: *Dickeya solani*, *D. dianthicola*, *Pectobacterium atrosepticum* and *P. wasabie* (project **C8**, final report, EUPHRESKO-I Dickeya report¹⁷).

Optimization of control

- **Alternative control**
 - Seed washing (soaking of the seed) increased threefold the occurrence of blackleg disease in potato. Due to technical issues, no conclusion could be drawn about the efficacy of ozone treatments on bacterial diseases on seed potatoes (project **C9**, final report). There has been no follow-up project.

1.4. Sugar beets

Nine projects were granted in the sugar beet system, five of which focused on IPM of BCN (*H. schachtii*). Integrated management of weeds (three projects) and leaf fungi (two projects) were also investigated in sugar beet systems. Additional projects related to soilborne fungi and free-living nematodes are discussed together in the soilborne disease section (II.1.5). Descriptions of the research findings and their implementation for projects targeting BCN are further described and analysed in section III.3.

1.4.1. Nematodes

The focus of the research projects was the prevention against BCN. A potential source of spread of BCN was investigated in one project (**D1**). The aims of other projects were to develop a DSSs (two projects, **D2** and **D3**) and to set-up variety trials focused on BCN resistance properties (two projects, **D4** and **D5**). The main achievements of the projects are summarized in Box 5, and further discussed in a specific section (III.3).

¹⁸ EUPHRESKO-I Dickeya report:
http://www.euphresco.net/media/project_reports/dickeyspp_final_report.pdf

Box 5: Main findings of IPM projects targeting nematodes in sugar beets

Prevention

- **Resistance**
 - BCN have higher propagation rates in normal sugar beet varieties than in tolerant or 'escape' varieties¹⁹ (project **D5**, final report).
- **Risk assessment**
 - Evidence that the use of digestate from biogas production that comes from sugar beet material as fertilizer does not spread BCN provided that digestates are stored before spraying (project **D1**, final report).
 - Swine slurry has the potential to inhibit the multiplication of BCN (project **D3**, final report).

Monitoring

- (Partial) development of BCN-Watch, a DSS for crop rotation planning in sugar beet production, with a focus on BCN management (project **D2**, final report).
- Improvement of BCN-Watch by defining the constants and variables for different resistance levels of sugar beet varieties (project **D5**, final report).

1.4.2. Fungi

Two projects focused on leaf fungi such as *Ramularia beticola*, *Cercospora beticola*, *Erysiphe betae* and *Uromyces betae* attacking sugar beets. Their main findings are summarized in Box 6.

Box 6: Main findings of IPM projects targeting fungi in sugar beets

Prevention

- **Resistance**
 - Importance of field evaluation to define the control threshold for fungicide treatment, otherwise relying solely on weather data (project **D6**, Olsson 2011; Olsson and Ekelöf 2015).

Optimization of control

- **Control frequency**
 - No clear conclusions could be drawn as to the effect of the number of treatments against leaf fungus in sugar beet on sugar yield and on leaf damage by fungi, and frost, as well as on the internal quality parameters of sugar beet due to small fungal pressure (project **D7**, Olsson and Persson 2012).

1.4.3. Weeds

Alternative and sustainable weed controls in sugar beets were investigated in two projects, with a focus on mechanical control (**D8**) and the development of precision control (**D9**). Their main findings are summarized in Box 7.

¹⁹ NBR defines Normal (N) variety as susceptible to BC, Tolerant (T) variety as able to limit yield suppression compared to a susceptible variety, without reducing the nematode reproduction, and Nematode Escape (E) variety as semi-tolerant to BCN. See section III.3. for more details.

Box 7: Main findings of IPM projects targeting weeds in sugar beets

Optimization of control

- **Alternative control**
 - Potential of inter-row hoeing to reduce herbicide use both in terms of effect and farm economy (project **D8**, final report).
 - (Partial) development of GPS and camera-guided mechanical control of weeds, which shows potential but still needs development (project **D9**, final report).

1.5. Mixed cropping

1.5.1. Weeds

Integrated weed management and tools for its implementation in major crops were investigated in twelve projects. Their main findings are summarized in Box 8. The research findings and their implementation are further described and analysed in section **III.4**.

Projects in sugar beet systems are described in their respective sections due to specific management strategies. Three of these projects had a particular focus on cereal systems, but their outcomes could potentially be used in other cropping systems.

Box 8: Main findings of IPM projects targeting weeds in annual crops

Prevention

- **Cultural practices**
 - Sowing with better synchronization with seed dormancy could reduce weed pressure. Here, black grass (*A. myosuroides*) density could be decreased by postponing sowing two to three weeks (project **F3**, final report).
 - Competitive properties of cultivars can lead to a significant reduction of black grass density, even without additional herbicide treatments (project **F3**, final report).

Optimization of control

- **Frequency of control**
 - Additional cultivation does not improve the level of couch-grass (*Elymus repens*) control achieved by a single cultivation during the early part of the post-harvest season in autumn (project **F2**, Ringselle 2015; Aronsson et al., 2015; Ringselle et al. 2015, 2016a).
- **Alternative methods**
 - Herbicide-free and resource-efficient couch-grass control can potentially be obtained with a site-specific approach accounting for the biomass level, using cover crops in association with mowing and/or row hoeing (project **F2**, Yesudasan 2013; Ringselle 2015).
 - Integrated weed control combining row hoeing and row spraying can provide efficient management and reduce the amount of herbicide sprayed (project **F4**, Nilsson et al. 2014)
 - Updates of the compensation point for thistle and sow thistle, which occurs before the recommended control threshold, so that mechanical control could be done accordingly before these stages (project **F5**, Tavaziva manuscript; Verwijst et al. manuscript).
 - Synergistic control effect when combining mechanical and chemical treatments used against black grass and broadleaf weeds in winter wheat. A selective weed

harrowing in autumn can reduce the use of chemical pesticides or enhance its effect (project **F6**, final report).

- **Economic considerations**
 - Labour and machinery costs might increase costs to an extent that is not compensated by a decrease in herbicide costs (project **N1**, final report). Further analyses are needed to confirm this pattern).

1.5.2. Soilborne pathogens

The study of soilborne pathogens in annual crops (cereals, oilseed rape, potato, sugar beets, as well as carrots) and in red clover was the focus of seven projects. Soilborne fungi and free-living nematodes were the target of four and three projects, respectively.

Soilborne fungi

SLU has coordinated and financed a thematic research programme: 'Biological Soil Mapping (BioSoM)', aiming to give scientific support towards a new service to farmers for detecting soilborne pathogens and advising in crop management to optimize crop rotation and production in Sweden. Many co-funders were involved, including Stiftelsen Lantbruksforskning and private industries. Stiftelsen Lantbruksforskning financed nine studies within the research programme. Of these, three studies are not included in this report: two initiated in 2007²⁰ and 2008²¹ and one is still ongoing²². One additional project (**E6**) was not part of BioSoM, and investigated sugar beet variety tolerance against soilborne disease.

The aims of the research projects were to develop detection methods, DSSs, and to identify resistant varieties and cropping systems to manage soilborne fungi, and particularly *Sclerotinia* spp., *Plasmodiophora brassicae*, *Verticillium* spp. in oilseed rape; *Gaeumannomyces graminis* in cereals, *Aphanomyces* spp., *Rhizoctonia* spp. in sugar beets, as well as *Fusarium* spp., *Cylindrocarpon* spp., and *Phoma* spp. in red clover. Their main findings are summarized in Box 9.

The findings from the BioSoM programme have partly been implemented in the industry with the creation of a soil testing service available at Eurofins²³. The service is based on soil analyses and provides guidance to farmers regarding the choice of cultivars. The service is also used in the planning of field trials.

²⁰ Stiftelsen Lantbruksforskning project H0744104: Impact of sugar beets on yield and quality in subsequent cereal crops [original title: Sockerbetornas effekt på skörd och kvalitet i efterföljande spannmålsgröda] (1.95 MSEK, Å. Olsson, 2012)

²¹ Stiftelsen Lantbruksforskning project H0833502: Biological Soil Mapping - integrated analysis of soilborne pathogens and soil chemistry in oil-crop, cereals and legumes- PHASE II [original title: Biologisk Markkartering- Integrerad analys av jordburna växtsjukdomar och markkemi i oljeväxter och stråsäd] (2.18 MSEK, A. Jonsson, 2013)

²² Stiftelsen Lantbruksforskning project H1160210: Rapid and accurate diagnosis of pathogens on red clover in soil and roots and heat sanitation of red clover seeds for improved seed quality [original title: Snabb och säker diagnos av rödklöverpatogener i jord och rot samt värmebehandling av rödklöverfrö för ökad utsädeskvalitet] (1.25 MSEK, A-C. Wallenhammar, ongoing)

²³ <http://www.eurofins.se/tjaenster/vaextodling/jord-sjukdomar/klumprot>

Box 9: Main findings of IPM projects targeting soilborne fungi in annual crops

Prevention

- **Mapping**
 - The fungi *V. dahliae* and *V. longisporum* are found in 13 % of soil samples where sugar beets present wilt symptoms (project **E5**, final report). *Fusarium* spp. (leaf fungi) was isolated in the leaves presenting wilt symptoms.
 - The risk pressure of soilborne fungi (*V. dahliae*) in sugar beets increases in fields for which crop rotation includes potatoes (project **E5**, final report).
- **Biology**
 - A correlation was found between the occurrence of *Verticillium* spp. and free-living nematodes (root-feeding and root-knot nematodes) (project **E5**, final report).
- **Resistance**
 - There is a need to account for the crops included in the crop rotation in the variety trials investigating resistance to soilborne fungi (project **E5**, final report).
- **Cultural practices**
 - Nitrogen fertilization at an early Chinese cabbage (*Brassica rapa* ssp. *pekinensis*) stage of development might reduce clubroot (*P. brassicae*) infection (project **E1d**, Nilsson 2014). Additional experiments are needed to confirm this pattern which might be generalized to be applied to the rapeseed system.

Monitoring

- **Monitoring methods**
 - Molecular methods to quantify *P. brassicae* DNA in soil samples (project **E1a**, Almquist 2016; Wallenhammar et al. 2012; Almquist et al. 2016a; Almquist and Wallenhammar 2015), to detect *Sclerotinia sclerotiorum* DNA in the context of a DSS against stem rot in oilseed rape (project **E1b**, Almquist 2016), and to detect and quantify the dominating soilborne pathogens in red clover (project **E1c**, Almquist et al. manuscript) were developed.
- **Forecasting**
 - Soil analysis can be used as a forecasting tool to assess the risk of damage by clubroot (*P. brassicae*) in oilseed rape (project **E1a/b**, Almquist 2016; Wallenhammar et al. 2012; Almquist et al. 2016a; Almquist and Wallenhammar 2015).
 - A DSS against stem rot in oilseed rape based on spore traps was developed (project **E1b**, Almquist 2016).

Optimization of control

- **Alternative control**
 - Thermal treatment of red clover seeds had no impact on pathogen pressure (project **E1d**, Almquist et al., 2016b).

Free-living nematodes

Preventive measures to manage free-living nematodes were investigated in three projects. They aimed at conducting an inventory of (**E7**) and developing detection methods (**E8**) for free-living nematodes in sugar beet fields (and carrots, **E8**). Project **E9** aimed at investigating the relation between damage by the pathogenic fungus *Rhizoctonia solani*

[other name: *Thanatephorus cucumeris*] and free-living nematodes. The results of this project do not have a direct implementation, but aim at increasing knowledge on the potential harmful impact of free-living nematodes. The main findings of these projects are summarized in Box 10.

Box 10: Main findings of IPM projects targeting free-living nematodes in annual crops

Prevention

- **Biology/Mapping**
 - The root-feeding nematodes present in all sugar beet growing areas were identified and their presence correlated with soil mineral composition and crop rotation (project **E7**, final report).
 - Wild herbivorous nematodes affect the growth of potato plants and can compromise harvest, to an extent depending on potato variety. Wild herbivorous nematodes for potato stem canker may result in further crop losses (project **E10**, Björsell et al. 2017; Edin and Viketoft 2017; Viketoft et al. 2017).

Monitoring

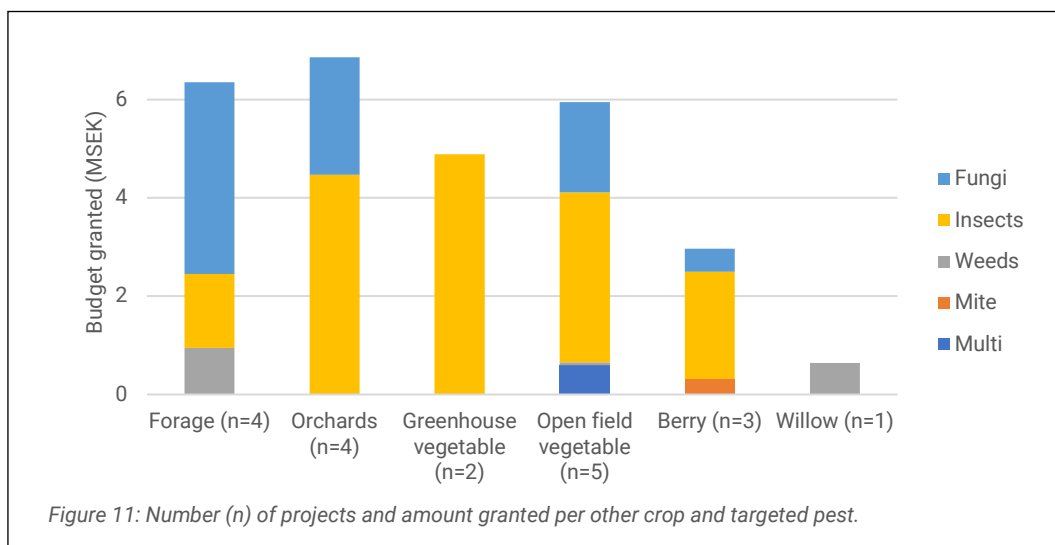
- **Monitoring methods**
 - An operational PCR-method to detect root-knot nematode (*Meloidogyne hapla*) and lesion nematode (*Pratylenchus neglectus*) in plant and soil material was developed. The methods for the detection of root-feeding nematodes (*Trichodorus* spp.) and stem nematode (*Ditylenchus dipsaci*) were partly developed and need further improvements (project **E9**, final report).

1.5.3. Compilation of knowledge

Five projects were funded to compile existing knowledge in the field of IPM. Each project resulted in the publication of a report in Swedish.

2. Other crops

A total of 20 projects for a total of 27.66 MSEK investigated IPM aspects in grasslands and forage, horticultural, and willow crops. The amount granted and pests targeted by the granted projects are summarized in Figure 11. All studies are listed in Appendix 4.



2.1. Grassland and forage crops

IPM aspects in grassland and forage crops (red clover, beans, and maize) were investigated in six projects. Their main findings are summarized in Box 11. The study of soilborne pathogens on red clover (project **E1c**) is presented in more detail in section **II.1.5.2**.

Box 11: Main findings of IPM projects in grassland and forage crops

Clover

Prevention

- **Breeding for resistance**
 - Two varieties of red clover adapted to Northern Sweden and showing good resistance properties against root rot and clover rot (*Sclerotinia trifoliorum*) were isolated (project **H1**, final report).
- **Biology**
 - Clover seed weevils (*Apion trifolii* and *A. fulvipes*) overwinter in and near former red and white clover fields. Female weevils preferentially feed on specific clover species: *A. trifolii* is specialist to red clover (*Trifolium repens*) and *A. fulvipes* on white clover (*T. pratense*) due to olfactory preferences. These new insights in clover seed weevil biology highlight the potential of olfaction traps to monitor and control the pests. In addition, preventive measures against clover seed weevils should include rotation of clover species at a regional scale (project **H2**, Andersson et al. 2012, Nyabuga et al. 2015).

Peas

Prevention

- **Biology**
 - A novel *Phytophthora* species (*P. pisi*) causing root rot in legume crops closely related to pea (pea, faba bean, lentil, common vetch, and chickpea) in Sweden was characterized (project **H3**, Heyman et al. 2012). *Phytophthora pisi* is relatively common in Sweden and appears to have a strictly soilborne life cycle.

Maize

Prevention

- **Preventive measures**
 - Intercropping organically-grown maize and faba bean slightly reduced weed incidence compared with mono-cropped maize, and can increase yield and protein content. In fields with relatively high amounts of available Nitrogen, it can additionally reduce the risk of N-pollution. Intercropping shows therefore potential for improving the sustainability of forage production (project **H4**, Stoltz and Nadeau 2014).

2.2. Horticultural crops

Investigations of IPM options or compilation of available knowledge of IPM in horticultural crops were the foci of 15 projects. The main findings of the projects are summarized in Box 12.

Box 12: Main findings of IPM projects in horticultural crops

Greenhouse vegetables (mainly cucumber)

Optimization of control

- **Optimization of application methods**
 - Manual spraying methods currently used in greenhouse production do not provide sufficient leaf coverage (particularly on the underside of the leaf) to insure sufficient protection. Available technology shows potential, but needs development to prevent plant damage (project **M2**, final report). Further development is ongoing²⁴.
- **Alternative methods**
 - Synthetic sunflower volatiles might be suitable as a tool to control the European Tarnished Plant Bugs (*Lygus rugulipennis*) in cucumber greenhouse production (project **I1**, Ondiaka et al. 2016; Rur 2016). The use of sunflower alone as trap crop does not provide a sufficient level of control.
 - Cucurbit Powdery mildew (*Podosphaera xanthii*) was successfully controlled by a combination of the biological control agent Sakalia® (formulated from the plant extract of giant knotweed, *Reynoutria sachaliensis*), and Yuccah (wetting agent from Yucca palm tree, *Yucca schidigera*) (projects **I1/M2**, Almqvist 2013; Rur 2016).

Efficacy of PPP used

- **Fungicide resistance**
 - Some strains of *P. xanthii* have become resistant towards Fungazil 100, the most commonly used fungicide in greenhouse cucumber production against Cucurbit Powdery mildew (project **I1**, Rur 2016).
- **Efficacy of PPP**
 - Sakalia® can successfully control cucurbit powdery mildew in greenhouse in Sweden (project **I1**, Rur 2016, Rur et al. 2017)
 - The predatory mites *Amblydromalus limonicus* commercially available for the control of thrips and whiteflies in greenhouse production negatively interact with another predatory mite species *A. swiirskii* at low thrips densities (project **I1**, Skytte af Sättra 2013).

Open field vegetables (carrots, turnips, onions)

Prevention

- **Biology**
 - Acrothecium is the major fungal disease of carrots in storage in Sweden, followed by white mould disease (*Sclerotinia sclerotiorum*). All cultivated varieties are sensitive to Acrothecium, in all growing region in Sweden. Depending on the variety, damage can increase with delayed harvest. Late harvest also increases damage incidence of carrot fly (*Psila rosae*) whereas an opposite pattern is observed with white mould disease, where higher damages are found at early harvest with no effect of variety (project **I4**, final reports).

Optimization of control

²⁴ Project H1356063 funded by Stiftelsen Lantbruksforskning: Application technology focusing on biological plant protection products [original title: Appliceringsteknik med fokus på biologiska växtskyddsmedel] (1.98 MSEK, K. Löfkvist)

- **Alternative control**
 - Fast emerging and developing carrot cultivars show potential to be used as catch crops to control carrot psyllids (*Trioza apicalis*). Sown before the main crop, they attract psyllids for reproduction, and their destruction before adult emergence and reduces pressure on the main crop. Further refinement of the techniques are needed to optimize sowing dates of the trap crop and main crop, and the choice of cultivars (project **I5**, Nilsson and Rämert 2017).
 - The use of insect nets in turnip plantations shows potential for controlling the cabbage root fly (*Delia radicum*) (project **I6**, final report).
 - Onion cultivation based on planted onions (compared to seeds) shows potential for reducing weed pressure and the need of chemical control (project **I7**, final report).

Orchards (apples)

Prevention

- **Biology**
 - Apple varieties show different susceptibility to fruit tree canker (caused by the fungus *Neonectria ditissima*). DNA-based molecular methods were developed to detect fungal infection (project **J1**, Garkava-Gustavsson et al. 2013, 2016; Ghasemkhani et al. 2015, 2016b, 2016a).
 - Losses during apple storage are mostly caused by fungal diseases, particularly in organic production. *Neofabraea* spp. and *Colletotrichum* spp. caused most damage in organic apples. Fungal species can be identified using molecular or visual methods. Differences in sensitivity are found between cultivars given their maturation time, with more damage found in early maturing varieties. Non-chemical post-harvest treatments with hot water or essential oils show potential for decreasing damage during storage (project **J2**, final report).
 - Tortricid moth densities increased in apple orchards after the ban on the broad-spectrum insecticide Gusathion® (active ingredient: azinphosmethyl), although other insecticides were used with no decrease in spraying intensity. A corresponding increase in crop damage was only observed with the leafroller moth *Cydia pomonella*. Variation in crop damage could be explained by the number and timing of insecticide applications, highlighting the need for an adequate forecasting tool for sustainable management of tortricids (project **J3**, Sjöberg et al. 2015).

Monitoring

- **Monitoring tools**
 - A kairomone was developed to monitor *C. pomonella* in apple orchards, resulting in the registration of a patent (project **J4**, Knudsen et al. 2012; Porcel et al. 2015).

Optimization of control

- **Decision support system**
 - A DSS for chemical control of tortricids in apple orchards was developed based on pheromone traps, weather data, and a questionnaire to farmers (project **J3**, final report).
- **Alternative control**
 - An IPM-strategy relying on a pheromone-based mating disruption technique was improved and showed potential for controlling insect pests in apple orchards (leafroller moths, including *C. pomonella* and *Spilonota ocellana*) to a similar or higher levels than in a sprayed control, with some variation between years and species. Additional experiments are needed to evaluate the efficacy of the product on *C. pomonella* (project **J4**, Knudsen and Tasin 2015). The socio-economic drivers have been identified as potential threats to the implementation of mating disruption techniques (project **J4**, final report).

Strawberry

Optimization of control

- **Control strategy**
 - Pest pressure in strawberry (fungi and insects) varies between years, and can be related to weather conditions and cultivars. Pest management in strawberry should be based on need-based control strategies (project **K2**, final report).
- **Application techniques**
 - Mechanical release of predatory mites (*Neoseiulus cucumeris*) against herbivorous mites (*Phytonemus pallidus*) is feasible with no damage. It increases the release capacity, reduces labour costs, and shows therefore potential for use in outdoor strawberry production (project **K3**, final report).

Efficacy of PPP

- **Alternative control**
 - The effects of the biological control agent Binab T (active agent: *Trichoderma* spp.) on fungal root diseases caused by *Phytophthora cactorum* and *Verticillium dahliae* vary according to cultivars (project **K1**, Khalil and Svensson 2017; Khalil manuscript).

2.3. Willow plantation

One project targeted the optimization of methods for termination of willow plantations, with impact on weed pressure, which could qualify for IPM. In this project, shallow cultivation was found to be an energy and labour-time friendly alternative method to fracturing stumps for termination of old willow plantations that shows no increase in weed pressure in the following crop (project **L1**, final report; Welc et al. manuscript).

3. Non-crop specific

Eight projects were not crop specific, focusing on broader topics such as the development of biostimulants, the study of the suitability of biological control agents in Sweden or general aspects of IPM. They are listed in Appendix 5.

3.1. Biostimulants and biopesticides

Three projects dealt with the development and/or the study of the suitability of biological control products in Sweden. The main outcomes are summarized in Box 13.

Box 13: Main outcomes of IPM projects targeting biological control products

Optimization of control

- **Alternative methods**
 - Thiamine enhances plant resistance against aphids under controlled conditions (project **M1**, Hamada and Jonsson 2013), so that there is a potential to develop methods for using thiamine as biostimulant to strengthen plant resistance in practical horticulture.
 - The suitability study of biopesticides available on the foreign market in Sweden has been found to be complicated because of (1) the low availability of such products and (2) the resistance from developing companies to see their products tested without being involved (project **M2**, final reports).

- **Application techniques**
 - The use of oil extracted from oilseed rape as an organic PPP would require a leaf coverage superior to 90 % (project **M3**, final report).

3.2. General aspects of IPM

General aspects of IPM or tools for IPM implementation were investigated in five research projects.

It is worth noting that constraints and opportunities for implementation of IPM at the farm level (project **N5**, final report) were identified. An IPM tool was refined to evaluate IPM implementation at the farm level, in the form of a questionnaire based on eight points:

- Farmers use preventive measures
- Farmers follow advice and have basic knowledge about pests
- Farmers implement a need-based pest management using diagnostic tools, advice, and control thresholds
- Farmers choose alternative and sustainable control methods if available
- Farmers safely use control methods
- Farmers use adapted dose and frequency, as minimal as possible
- Farmers implement measures to reduce the risk for resistance
- Farmers assess the outputs of methods used.

The need for improvements in communication and advisory services with inputs from demo-farms to promote IPM adoption was emphasized. Particularly, the following needs were identified: (1) increase availability of additional advice and information on IPM implementation to farmers, (2) expand forecast and alert services activities and incentives to improve their adoption by farmers and advisors, and (3) promote the availability of information on variety characteristics for disease resistance levels.

4. Discussion: granted projects and outputs

Most research projects targeted IPM in major crops such as cereals, potato, oilseed rape, and sugar beet, and to a lesser extent IPM in a few forage and horticultural crops. Large investments were made for research on a few specific pests, namely FHB, potato late blight, BCN and weed control. Strength and weaknesses of the research projects in major and minor crops are discussed below.

4.1. Major crops

The research projects investigating IPM in major crops all align reasonable well with the targets of the different announced calls. The development of monitoring methods for researchers, field trials, advisory services and farmers, among other R&D projects, were investigated. All stages of the knowledge chain are found, from applied research, concept development and proof of concept (often in collaboration with national field trials), as well as compilation of knowledge and studies on the suitability of existing methods. Some projects had an excellent scientific approach, from replicated design to analysis and interpretation of results, and provided evidence-based results that could support targeted measures or recommendations in both the short- and long terms. Such work is often published (or at the manuscript stage) as a peer-reviewed scientific article and summarized for stakeholders in archived fact-sheet. In contrast, some other projects had a weaker scientific approach, and provided results based on a small number of replications and were rarely supported by any statistical analyses, which can call into question their validity. Particularly, projects aiming at developing methods for field trials or at studying economic returns were sometimes limited in their scientific approach. In addition, a few projects could not achieve their goals due to technical/ methodological constraints or have deviated from the initial, applied focus due to methodological constraints. For example, research on the

suitability of biological control agents not registered in Sweden has faced reticence from industry to provide such agents.

Most studies were of high relevance for the agricultural sector, and aimed for quick implementation in a relatively short term. However, no specific timeframe for implementation was defined in any of the final reports. Some projects were funded at an early stage in the development of novel sophisticated method, with a lower chance of result implementation within a short timeframe. An investigation of implementation of research projects targeting the four major pest/crop systems (FHB, potato late blight, BCN and weeds in arable crops) is done in section III.

Strengths and weaknesses of IPM research in major crops are summarized in Box 14.

Box 14: Strengths and weaknesses of research projects in major cropping systems	
<p>Strengths</p> <ul style="list-style-type: none"> • High relevance of research for the sector • Good collaboration with industry and/or advisory services and/or national field trials • High scientific quality of some research projects, assessed by peer-reviewed publications in international journals and clear evidence-based recommendations communicated through popular channels with long-term accessibility • Some European and international collaborations 	<p>Weaknesses</p> <ul style="list-style-type: none"> • Weak scientific approach/outputs of some applied research projects, sometimes funded through multiple applications • Some specific targets of the calls have not found answers, particularly due to a lack of projects developing or leading to full product development of: <ul style="list-style-type: none"> – alternative control methods (e.g., biopesticides, crop engineering), and absence of full product development – economically viable strategies to prevent and manage pesticide resistance • Lack of approaches using: <ul style="list-style-type: none"> – farmer and consumer involvement (participatory approaches) – holistic and multi-year perspectives – a focus on socio-environmental and economic value of IPM • Absence of coordination and/or collaboration between/with: <ul style="list-style-type: none"> – research projects dealing with different aspects of IPM in a same system – scientists and advisory services for method development and research projects within field trials – EU-projects

Overall, the need for improved quality of the research projects is warranted. In addition, coordination between research projects aiming at the same target, and between research projects and national field trials is highlighted. Also, a more systemic approach to pest

management seems highly motivated. In addition, some of the research projects targeted themes in accordance with priorities defined at the European level²⁵. The latter were categorised in the two core themes for future IPM research in Europe: Preventive measures for sustainable pest management and Alternatives to conventional pesticides and innovative control (Messéan 2016). This underlines the need for more European/international collaboration and visibility which were found lacking for many projects.

4.2. Other crops

Projects dealing with IPM in other crops such as forage crops, horticultural crops, and willow production varied in their aim, profile, and targeted systems. A few systems in both open field and greenhouse production were targeted, all characterized by a small cultivation area and few stakeholders. These systems generally suffer from a reduced availability of PPPs on the Swedish market, which make them rely heavily on the development of alternative strategies and implementation of IPM practices.

Many research projects within other crops have resulted in developed products/strategies, which could be further tested/adopted by farmers. Some of the research projects showed a strategic plan from research to implementation, and were often carried out in collaboration with growers. Some projects in horticultural crops have been designed in collaboration with growers, who could provide feedback to researchers throughout the duration of the project. Although not directly analysed in this report²⁶, such project specificities might have resulted in a willingness from farmers to adopt newly designed practices. Feedback from researchers is promising, describing high interest from farmers. However, the cost of alternative control methods was highlighted as a threat to implementation.

Some of the research projects targeted a priority area in minor use in Europe (Kiss 2016), which further emphasizes the need for more European/international visibility that is lacking for many projects. Similarly, few, if any, breeding activities or variety trials were undertaken by the research projects targeting minor uses. A similar picture is found at the European level (Messéan 2016).

Strengths and weaknesses of IPM research in forage and horticultural crops could be identified (Box 15).

²⁵ Conclusions from the European ERA-NET project C-IPM (Coordinated Integrated Pest Management in Europe)

²⁶ Interviews regarding implementation of research findings were only done for research in four targeted pest/crop systems, all in major crops.

Box 15: Strengths and weaknesses of research projects in forage and horticultural crops

Strengths

- High relevance for the sector
- High scientific quality of some research projects
- One patent filed
- Systemic approach used in most projects, with a good integration of different aspects of IPM
- Participatory approach, and sometimes good collaboration with advisory services and industry

Weaknesses

- Weak scientific approach/outputs as well as lack of international visibility for some projects
- Only a few systems targeted, and some specific knowledge gaps targeted by the calls have not found answers
- Lack of economic valuation

III. Specific Research Areas

Due to their strong economic importance, the specific research areas of (1) FHB in cereals, (2) potato late blight, (3) BCN in sugar beets, and (4) weed management in arable crops are reviewed in more detail below. The problem is introduced and findings of the research projects are presented in detail. The implementation of research results at different levels (research, industry, advisory services, field trials, farming practices) is also discussed, based on interviews with researchers and advisors.

1. Fusarium head blight and DON mycotoxin contamination in cereals

Fusarium head blight (FHB) is one of the major fungal disease of cereals (Leplat et al. 2013). It is caused by a complex of different *Fusarium* species (principally *F. graminearum* [sexual stage also named: *Gibberella zeae*], *F. langsethiae*, and *F. culmorum*). FHB can reduce yield by up to 60 % as observed in the EU during the period 2003–2007 and an average of 0.5 to 28 % according to individual countries²⁷. In addition, FHB produces mycotoxins such as deoxynivalenol (DON), zearalenone (ZEA), T-2 and HT-2²⁸, and Nivalenol²⁹ (NIV). These mycotoxins, of which DON and ZEA are produced by *F. graminearum* and *F. culmorum*, accumulate in the grain and represent threats to human and livestock health. EU-regulations have established maximum tolerated levels in grain in 2007 (Appendix 6, except NIV).

DON causes nausea, vomiting, and diarrhoea in humans (Shipton 2014 p. 52), as well as abdominal pain, headache, dizziness and fever (Sobrova et al. 2010). In animals, exposure is typically associated with feed refusal, weight loss, and suppression of the immune system (Shipton 2014 p. 52) and similar effects are suspected in humans. ZEA is a livestock teratogen (Shipton 2014 p. 52) and might play a potential role in the risk of developing breast cancer in humans (Belhassen et al. 2015). Pigs show the highest sensitivity to T-2 toxin, DON, and ZEA. Poultry are sensitive to both DON and T-2 but show good resistance to ZEA. Ruminants are less sensitive to mycotoxins although extensive exposure can affect production, growth, and reproduction (Zain 2011). Transmission from animal to products such as eggs and milk has been found to be negligible although this risk may not be totally excluded (Sobrova et al. 2010). Most research studies focus on *Fusarium* pressure and DON, but a correlation between ZEA- and DON-contents could be found (Rossi et al. 2007) so that results may most likely be generalized to both mycotoxins.

In the western parts of Sweden, growing problems with DON-levels above the threshold values have been registered. Large volumes of wheat and oats were not suitable for human consumption (Fredlund et al. 2013; Lindblad et al. 2013; Wiklund 2017) and even for animal feed³⁰ in the past years. Large losses of oats were reported in 2011, when an important part of the harvest was rejected for human or animal consumption and therefore sold for biogas production because of high mycotoxin levels (O. Sixtensson, personal communication). These rejections were based on visual observation of pink kernels as an indication of *Fusarium* infection or DON-analysis done at cereal delivery³¹. Mycotoxin content can vary drastically even within the same region or field, so that analyses are often needed at the load level, which is time consuming and costly (Lindblad et al. 2013). This calls for predictive models of DON-levels that enable early prediction in order to generate reliable estimates of mycotoxin levels in grains (Rossi et al. 2007).

²⁷ ENDURE deliverable D1.2 (2008): Best control practices of diseases in winter wheat (p.18). Retrieved from http://www.eurowheat.org/upload/eurowheat/document/ENDURE_wheat_case_report.pdf

²⁸ T-2 and HT-2 mycotoxins are produced by *F. langsethiae* and *F. sporotrichoides*

²⁹ NIV is primarily produced by *F. avenaceum*

³⁰ Oats, L. Johansson, report from Jordbruksverket, 2012-10-15

³¹ Lantmännens Gårdsmagasinet 2014

Jordbruksverket publishes yearly a description of the risks for FHB and a decision key to help evaluate the risk level for DON at the field level. In 2008, the weather, and especially the rain during the blooming season, as well as farming practices with the presence of crop residues and the type of preceding crop were presented as major factors in the risk assessment of mycotoxin-producing *Fusarium*. The factors have been updated yearly in collaboration between academia, industries, and advisory services. The use of less susceptible varieties, of preventive cultivation practices (e.g., rotation, tillage, fertilization, weed management, timing of harvest and crop lodging), and, if needed, chemical control are recommended by Jordbruksverket to prevent and control FHB in cereals. For the last alternative, two fungicides are registered in Sweden against FHB in cereals: Proline EC 250 (active substance: prothioconazole 250 g/l, for wheat, rye, triticale, oat, barley, oilseed rape and turnips) and Topsin WG (active substance: Thiophanate-methyl 70 w-%, for winter wheat, rye and winter barley). Data on fungicide use specifically against FHB could not be obtained. Generally, the extent of fungicide treatment in cereals crops differed according to growing region and crop³². Fungicide treatments were most common in wheat (particularly winter wheat) and in Skåne (with fungicide treatment in >80 % of cereal acreage). In contrast, fungicide treatments in oats were infrequent, applied in an average of 9 % of the oat acreage over the country.

1.1. Research projects funded by Stiftelsen Lantbruksforskning and Jordbruksverket

A total of 12 applications have been granted during the period 2009–2014 that targeted IPM against FHB in cereals (alone or combined with other cereal fungi), for a total of 16.16 MSEK (Table 2).

Table 2: Research projects dealing with integrated management of FHB in cereals funded by Stiftelsen Lantbruksforskning and Jordbruksverket during the period 2009–2014. Additional applications funded within a research project are mentioned [italicized, in grey] in the table. All studies with the same identifying number (#) constitute a single research project.

Call: year of application; Final: year of publication of the final report.

	#	Title (Institution)	Research category	Budget MSEK	(Call) Final
Prevention	A1	Characterization of <i>Fusarium</i> resistant oat (CropTailor/LU)	Breeding	2.20	(2011) 2013
	(A1)	<i>New oat for the food industry (LU, project number O-15-20-346)</i>	<i>Breeding</i>	<i>3.50</i>	<i>(2015)</i> -
	A2	Development of genetic markers for resistance, quality, and value for cultivation of oats (Lantmännen)	Breeding	2.20	(2009) 2014
	(A3)	<i>Pilot project for testing wheat and triticale varieties for Fusarium sensitivity (Lantmännen, project number H0860020)</i>	<i>Variety trials</i>	<i>0.71</i>	<i>(2008)</i> 2013
	A3a	Pilot Project - Development of methods for testing the wheat and triticale varieties of <i>Fusarium</i> sensitivity and toxin production (Lantmännen)	Variety trials	0.50	(2010) 2010
	A3b	Testing of wheat and triticale varieties of <i>Fusarium</i> sensitivity and toxin production (Lantmännen)	Variety trials	0.05	(2011) 2012
	A3c	Continued testing of <i>Fusarium</i> susceptibility of wheat- and triticale varieties and pilot testing of <i>Fusarium</i> susceptibility of oats and barley varieties (Lantmännen)	Variety trials	0.60	(2012) 2014
	A8	Towards IPM in wheat: Persistence of stem base pathogens on crop residues (SLU)	Biology	1.98	(2009) 2015
	A9	Development of plant diseases in future cropping systems with maize and winter wheat (SLU)	Biology	1.25	(2010) 2015
	A11	Seed transmittance importance of spreading the DON-producing organism <i>F. graminearum</i> (SLU)	Risk assessment	0.13	(2013) 2013

³² Plant protection products in agriculture and horticulture. Use in crops. Statistiska meddelanden No. MI 31 SM 1101. MI - Miljövärd och naturresurshushållning (SCB 2011).

Monitoring	A4	Quick and reliable detection of <i>F. langsethiae</i> with the "Loop-Mediated Isothermal Amplification" method (HS)	Method detection	0.67	(2013) 2015
	A15	Prediction of plant diseases based on molecular methods and spore traps (SLU)	Method detection	2.13	(2012) 2016
	(A15)	Leaves as spore traps for improved forecasting methods (SLU, project O-16-20-767)	Method detection	3.00	(2016) ongoing
Optimization	A10	Prediction of deoxynivalenol (DON) in oats in western Swedish conditions using weather crop and management data (Lantmännen)	Forecasting	2.10	(2011) 2015
	M2	Bio-evaluation - Are biological control products that are available on foreign markets usable against plant diseases in Sweden? (Maselaboratorierna AB/SLU)	Alternative methods	2.30	(2011) 2016

1.2. Advances in Swedish research

1.2.1. Prevention

Risk assessment

In project **A8**, Friberg et al. (final report [a]) investigated the development of stem base pathogens on different rotation regimes for which frequencies are expected to increase in Sweden due to change of climate and of cultural practices. In project **A9**, Friberg et al. (final report [b]) investigated pathogen persistence on cereals residues. Stem base pathogens causing FHB (*F. graminearum*: projects **A8** and **A9**, and *F. culmorum*: project **A9**), and causing eyespot (*O. yallundae*: project **A8**) were targeted by the projects. The persistence of stem base pathogens on crop residues and the importance of agricultural practices for disease development has been reviewed (Leplat et al. 2013) and the effect of tillage practices, host plant, and crop rotation have been tested in field trials (Friberg et al., final reports). These reports pointed out the importance of the following factors:

For pathogen survival:

- Preceding crop
 - A preceding crop with a low Carbon/Nitrogen (C/N) ratio and high amount of crop residues enhances *F. graminearum* survival. The risk of pathogen infection is therefore higher when cereals are grown after maize which has both low C/N ratio and, when grown for grains, also leaves large amount of residue (Leplat et al. 2013).
 - DON quickly disappears through adsorption or degradation in crop residues (-43 to -50 % after five weeks and -90 % after 17 weeks in maize residues), and does not impact the development of *Fusarium* in the next crop (Abid 2012, Chap. III, project **A8**).
- Presence of antagonists:
 - The survival of *F. graminearum* can be limited by the action of antagonistic micro-organisms such as *Trichoderma atroviride*, *T. harzianum*, or *Clonostachys rosea* (Leplat et al. 2013).
- Soil fauna:
 - Earthworms can reduce the quantity of pathogenic fungi (Leplat et al., 2013). In addition, Abid (2012, Chap. IV, project **A8**) showed that the presence of earthworms was associated with the disappearance of DON from crop residues: a 40-fold reduction of DON-concentration of crop residues left at the soil surface was observed in the presence of earthworms compared to when earthworms were absent.

For pathogen development:

- Preceding crop:
 - The risk of pathogen development increases with the nature of the preceding crop as a host and substrate for the pathogen. Maize as preceding crop represents a high risk, as well as wheat monoculture in comparison to after wheat-pea or wheat-fallow to

wheat-durum than after wheat or barley (Leplat et al. 2013). This was confirmed by field experiments in Sweden that showed that the risk of *F. graminearum* development (both asexual reproduction, with the production of macroconidia and sexual reproduction, with the production of perithecia and ascospores) was higher in maize straw than in winter wheat straw (Friberg et al., project **A9**, final report [b]); and in monocultures of host plants (Friberg et al., *Id.*). Although this situation is currently not a risk in Sweden where maize is almost exclusively used for silage, with very little crop residues left in the field, this could present a risk in the future in case maize production for human consumption increases and more residues are left in the field after harvest of cobs. Furthermore, this project gave the first evidence of sexual reproduction occurring in Sweden, and suggested a longer survival time of *F. graminearum* inoculum in the soil than initially assumed. Ascospores were still produced from crop residues in the same numbers after two years while nearly no conidia were produced in the second year (Friberg et al., *Id.*).

- Tillage:
 - Inversion tillage reduces the risk caused by *F. graminearum* by (1) hiding the primary inoculum, (2) enhancing the decomposition process and limiting pathogen survival, and (3) controlling weeds which could be a source of inoculum (Leplat et al. 2013). This pattern was observed for the intensity of winter wheat discoloration with both wheat and oat as preceding crop but not with oilseed rape and peas (Friberg et al., project **A8**, final report [a]).
- Fertilizers and herbicides:
 - So far, there are indications that inorganic Nitrogen fertilization and calcium ammonium nitrate may increase the risk of *Fusarium* infection (compared to organic fertilization with urea). Similarly weed control with Glyphosate might enhance fungal development, whereas weed control could potentially reduce the risk coming from additional inoculum sources. Organically-produced cereal grains have a lower (Birzele et al. 2002; Meister 2009; Bernhoft et al. 2010) or equal (Edwards 2009) level of *Fusarium*-generated mycotoxins in the EU (Leplat et al. 2013).
- Treatment of straw residues:
 - The growth of *F. graminearum* can be limited by the action of antagonistic micro-organisms such as *Trichoderma atroviride*, *T. harzianum*, or *Clonostachys rosea* (Leplat et al. 2013). Perithecial production by *F. graminearum* on straw residues was significantly and drastically decreased (-60 to -90 %, depending on dose and treatment) when treated with the antagonist fungus *C. rosea* (Jørgensen 2014; Friberg et al., project **A8**, final report [a]), so that such treatment of crop residues and/or seeds could potentially reduce pressure from *F. graminearum* in cereals. An assessment of the economic feasibility of such treatment would, however, be needed. Treatment with the bacteria *Pseudomonas chlororaphis* showed no effect on perithecial production by *F. graminearum* (Friberg et al., *Id.*).

Resistant varieties

Breeding for resistance

The aim of projects **A1** and **A2** was to improve breeding techniques and develop molecular markers for disease resistance in oats. Two different methods were used:

- 1) The use of mutagenized populations to develop resistant varieties and proteomic analyses of the *Fusarium* infection process (project **A1**)
- 2) The use of association mapping of a large set of different phenotypes obtained worldwide to develop molecular markers (project **A2**). A large spectrum of traits was investigated: (i) disease resistance to nematodes, crown rust: *Puccinia coronata*, smut: *Ustilago* spp., powdery mildew: *Blumeria graminis*, and *Fusarium*, (ii) agronomic traits such as yield, straw length and strength, maturity, and (iii) quality traits such as protein, beta-glucan, and fat content.

Using laboratory and field experiments during two years in one location on 2,300 lines developed by mutagenized populations initiated from the variety Belinda, some ten *Fusarium*-resistant lines were identified using DON-analysis from inoculated lines in field experiment (Olsson, project **A1**, final report). Proteomic analysis of both resistant and susceptible commercial varieties enabled the identification of potential molecular markers for *Fusarium* resistance (Olsson, *Id.*; Olsson 2014 [MSc thesis]). Ongoing research further *investigates* these identified resistant lines to develop molecular markers for *Fusarium* resistance (project O-15-20-346, Table 2).

Using laboratory and field experiments, line characteristics (such as disease resistance) were assessed over two years for 600 oat lines collected worldwide. *Fusarium* resistance was assessed by DON-analysis based on natural field infection (A. Ceplitis, personal communication). Using an association mapping, i.e., comparing phenotypic characteristics to a database of molecular markers, Ceplitis identified molecular markers for all studied properties (including *Fusarium* resistance) except resistance to nematodes and smut disease (project **A2**, final report).

Variety trials

Variety trials for wheat and triticale resistance against *Fusarium* were initiated in 2009 (project H0860020, Table 2), and received additional financing yearly until 2012 from either Stiftelsen Lantbruksforskning or Jordbruksverket (project **A3**). The trials were later extended to oat and spring barley. The methods for crop irrigation, *Fusarium* inoculation, and DON-analysis were established to provide good conditions for fungal development and measurement of *Fusarium* resistance properties. There seems to be important variation between varieties, and variety properties seemed relatively constant between location and years. No analyses were published that supported these patterns. These trials were later included into national field trials in 2016 for winter- and spring wheat, and oats (Sixtensson, personal communication).

A 'loop-mediated isothermal amplification' PCR method targeting *F. langsethiae* was partially developed monitor infections in field trials (Omer et al., project **A4**, final report), but the method still needs improvement before implementation (Z. Omer, personal communication).

1.2.2. Monitoring Prediction of DON-content

Large regional variation in DON-content in oats is observed in Scandinavia. Early attempts to develop risk assessment for DON in Scandinavian could not predict DON-content in oats based on a regression model accounting for the effect of weather variables (rainfall, temperature) and agronomic variables (soil types, cultural practices, flowering period and harvest time) (Lindblad et al. 2012).

Börjesson et al. (project **A10**, final report) aimed at developing a prediction model for DON-content in Scandinavian oats based on weather and phenological data. Börjesson et al. (*Id.*) adapted previously published mechanistic models that had been initially developed for wheat and barley in Northern Italy (Rossi et al. 2003) and for wheat in Brazil (Del Ponte et al. 2005) to Scandinavian oats. These published models are based on weather data collected during the period when the crop is most sensitive to infection. Model parametrization with oat characteristics (particularly sensitivity period) in Swedish conditions was needed to adapt these models to oats. Börjesson et al. (*Id.*) characterized the oat sensitivity period to *Fusarium* using field observations. This period was shown to be spread over up to four weeks after the first blooming ear was observed, with slight variation according to oat variety. The flowering period could be predicted using day-degrees. The new parametrized model developed in the project could predict a part of the variation of DON-content in oats in western Sweden at harvest using weather data (temperature, precipitation, relative humidity, wind speed and direction) (Börjesson et al., *Id.*). Using three-year data from sowing to harvest, 70 % of the variation in DON-content (Standard-error of cross validation: SECV=522 µg/kg grains) could be determined by the model (Persson et al. 2017). This

project has initiated new collaborative work to improve model predictions within the EU-interregional programme Öresund-Kattegatt-Skagerrak (ÖKS)³³. Additional collaboration with national advisory services (Jordbruksverket) is ongoing to complement the weather-based risk index with agronomic factors.

Yuen et al. (project **A15**, final report) investigated the use of spore traps as mean to detect fungal diseases. A comparison of different traps (passive and active) was made and analytical methods (DNA sequencing and analysis) were developed. Differences between traps and their placement, as well as between analytical methods were found. An active suction trap (Hirst trap) was shown to be the most precise trap to detect fungal pathogens. They found that trap placement was important, so that traps placed at a low height gave a better overview of the fungal community at the field scale, while traps placed at a higher height cover the community from a larger area. The comparison of different analytical methods showed that sequencing by PacBio RSII (Pacific Biosciences of California, Inc.) was the most reliable, whereas rare species were better detected using MiSeq (Illumina Inc.). The former is therefore recommended for future studies of fungal communities, although the use of species-specific primers for (q)PCR would be better suited for studies focusing on specific species, such as, for example, for pest monitoring. (A. Berlin, project **A15**, personal communication). *Fusarium* was one of the fungal families detected in cereal fields as early as early June. Further developments are needed to enable identification to the species level. Further analyses are needed to assess whether such detection can be correlated to actual field observations carried by the Plant Protection Agency (PPA, växtskyddscentralen), and therefore be used to improve monitoring and forecasting of fungal pathogens such as *Fusarium* in the fields.

Infected seeds as disease vectors

Persson et al. (project **A11**, 2014) investigated the possibility that infected seeds could be at the origin of the spread of *F. graminearum* in Sweden. Data show that contaminated seeds can introduce *F. graminearum* to new areas and therefore be at the origin of the spread observed in Sweden. The use of clean seeds (e.g., thermos-treated) seeds is therefore recommended.

1.2.3. Alternative methods

Hökeberg (project **M2b**, final report) investigated the suitability of biological control products registered and used in foreign markets for the Swedish market. Among others, the effects of the broad spectrum antagonistic fungi *Pythium oligandrum* and *Clonostachys rosea* were assessed against *Fusarium* in winter wheat. Biopesticides were used as seed treatments and tested under field conditions. The experiment could not draw conclusions about the tested antagonistic fungi on *Fusarium* due to low field infestations. The data however highlight the difficulties in testing biological control products that are not registered in Sweden due to reluctance from developing companies and suggest future studies to be done in collaboration with Swedish resellers.

1.3. Additional field trials

Additional field trials targeting *Fusarium* prevention and control, as well as DON-reduction have been carried out as part of the national field trials or contracted by Jordbruksverket (coordinated by the PPA). Particularly, the efficacy of fungicides to control *Fusarium*³⁴ and on DON³⁵ has been carried out in winter wheat and oats³⁶. A significant reduction of 33 % in average DON-content was observed in loads treated with Proline (to 525 µg/kg³⁷), but no reduction of *Fusarium* could be detected after treatment with Topsin under weak fungal pressure³³. Proline has additionally been included in fungicide trials against black spot and

³³ Innovation for sustainable crop production [original title: 'nnovationer för hållbar växtodling], co-financed by Lantmännen and the Swedish region Västra Götaland

³⁴ *Proline* and *Topsin*, trial L15-1042-09, Gustafsson, Jordbruksverket (2009)

³⁵ *Proline*, trial L15-510, Johansson, Jordbruksverket; and Roland, HS (2009)

³⁶ Field trials reports for Central Sweden [original title: Försöksrapport Mellansverige] (Sverigeförsöken 2012)

leaf spot diseases in winter wheat and winter and spring barley for which no measure of DON-content was taken. As of 2016, no trials are testing the effect of Topsin, also registered against FHB.

Variety trials with a focus on *Fusarium* resistance have been carried out on wheat (winter and spring) and oats in Skåne (all three crops) and Central Sweden (spring wheat and oats) in 2016. Results from trials in Skåne suggest some difference in resistance properties between varieties whereas field trials in Central Sweden encountered some technical issues with irrigation and suffered low *Fusarium* pressure³⁷. No analyses (variation within treatment and across locations) were provided. In addition, field trials have highlighted a large within-field variation in DON-content which might question the current technique to monitor DON-content at cereal delivery. They also found a positive correlation between DON-content and clay as well as other mineral (magnesium, copper and potassium) content in the soil³⁸. The literature suggests that soil type affects DON-degradation by microorganisms, with a slower degradation in clay soil (Wolfarth et al. 2013), but the link between high DON-content in soil residues and future problems is questioned (Abid 2012). The effect of seedling density in controlled environment (irrigation) and its economic feasibility on DON-content was additionally investigated, and no difference was observed between densities varying from 100 to 700 seeds/m². As of 2016, however, there have been no field trials on the effect of cultural practices such as crop rotation or tillage on *Fusarium* pressure or DON-content, or field trials targeting organic production.

1.4. Communication

Results from seven out of eight projects have currently been reported in the final report alone, and communicated in the trade press (e.g., Lantmännen, Arvensis). So far, one peer-reviewed publication (project **A8**) and two conference proceedings (projects **A2** and **A11**) have been published. Two projects have further contributed to undergraduate and graduate education with the publication of one PhD thesis (for which scientific support was provided through project **A8**) and two MSc theses (projects **A1** and **A8**). Four additional projects are planning additional publications. Means of communication are summarized in Table 3.

Table 3: Publications and communication of results [1: presence, in addition to final reports] from projects with a focus on *Fusarium* funded by Stiftelsen Lantbruksforskning and Jordbruksverket in the period 2009–2016. In light green: published and searchable publication. In orange: publication/communication channels not found online. In red: no publication/communication found.

	Popular publication		Peer-reviewed	Scientific publication		Conference		Education	
	Online	Print		Conference proceeding	Manuscript	National/regional	International	PhD	MSc/BSc
A1		1		1	1	1	1		1
A2					1		1		
A3		1				1			
A4						1			
A8	1	1	1		1	1	1	1	1
A9		1			1	1			
A10					1	1			
A11				1			1		
A15					1	1	1		
M2b					1	1			

³⁷ Field trials reports for Skåne [original title: Skåneförsök] (Sverigeförsöken 2016)

³⁸ High levels of DON-mycotoxin - threat to the Western Swedish oat cultivation? [original title: Höga DON-halter – hot mot västsvensk grynhavreodling?] (Roland, HS, 2016)

Peer-reviewed publication

Leplat, J., Friberg, H., Abid, M. & Steinberg, C. (2013) Survival of *Fusarium graminearum*, the causal agent of Fusarium head blight. A review. *Agronomy for Sustainable Development* 33:97–111. [Project **A8**]

Conference article

Persson, P., Bökter, H. & Friberg, H. (2014) Seed borne *Fusarium graminearum* in cereals – introduction to new areas. In NJF report. Presented at the Nordic Baltic Fusarium Seminar, Helsinki, NJF report 9 (8):13. [Project **A11**]

PhD thesis

Abid, M. (2012) Ecological role of mycotoxins produced by *Fusarium graminearum*: Consequences of the presence of deoxynivalenol (DON) in crop residues on the soil microflora and soil fauna. PhD thesis, Université de Bourgogne (Dijon, France). [Project **A8**]

MSc theses

Jörgensen, K. (2014) Biological control of *Fusarium graminearum*. MSc thesis, SLU (Uppsala, Sweden). In Swedish [Project **A8**]

Olsson, J. (2014, unpublished) Proteomics comparison of resistant and susceptible oat varieties to reveal proteins involved in resistance. MSc thesis, Lund University (Lund, Sweden). [Project **A1**]

Final reports

Börjesson, T. (2010) Pilotprojekt för provning av vete- och ragvete-sorters *Fusarium* känslighet. Final report for Jordbruksverket 6312. [Project **A3**]

Börjesson T., Persson T., Eckersten H., Pettersson C-G., Elen O., Hjelkrem A-G.R. (2015) Prediktering av Deoxynivalenol (DON) i havre under västsvenska förhållanden med hjälp av väder- gröd- och skötseldata. Final report for Stiftelsen Lantbruksforskning number H1133251. [Project **A10**]

Ceplitis, A. (2014) Utveckling av genetiska markörer för resistens, kvalitet och odlingsvärde i havre. Final report for Stiftelsen Lantbruksforskning number H0936280. [Project **A2**]

Djurle, A. (2015) Kartläggning av resistens mot svartpricksjuka i vete och interaktioner med odlingsmiljön. Final report for Stiftelsen Lantbruksforskning number H10333263. [Project **A7**]

Friberg, H., Persson, P. & Jensen, D. F. (2015a) Med sikte på IPM i vete: Överlevnad av stråbaspatogener på växtmaterial. Final report for Stiftelsen Lantbruksforskning number H0933214. [Project **A8**]

Friberg, H., Persson, P. & Jensen, D. F. (2015b) Utveckling av växtsjukdomar i framtida odlingsystem med majs och höstvete. Final report for Stiftelsen Lantbruksforskning number H1033190. [Project **A9**]

Hökeberg, M. (2016) Biovärdning – är biologiska bekämpningsmedel från utländska marknader användbara mot svenska växtsjukdomar. Final report for Stiftelsen Lantbruksforskning number H0956299. [Project **M2b**]

Olsson, O. (2013) Karakterisering av *Fusarium*-resistent havre. Final report for Stiftelsen Lantbruksforskning H1133073. [Project **A1**]

Persson, P. (2013) Utsädesmittans betydelse för spridningen av den DON producerande skadegöraren *Fusarium graminearum*. Final report for Jordbruksverket number 10551. [Project **A11**]

Yuen, J. & Berlin, A. (2016) Prognos av växtsjukdomar baserad på molekylära metoder och sporfallor. Final report for Stiftelsen Lantbruksforskning number H1233053. [Project **A15**]

1.5. Implementation

1.5.1. Industry

The two projects dealing with improving breeding techniques for variety resistance (**A1-A2**) have been done in close collaboration with the industry. Although further work is needed to

achieve the development of new, resistant varieties, project **A1** has initiated follow-up projects to meet this goal (O. Olsson, personal communication). Project **A2** has contributed to the development of a new oat breeding programme based on genomic selection at Lantmännen, Sweden. This method, used for example in animal breeding, is based on genotyping large numbers of breeding lines for which genotypes (including disease resistance traits) can be predicted earlier in the breeding cycle using statistical methods (Ceplitis, personal communication). Some of these results have therefore already been implemented by the industry and have contributed to improving oat breeding techniques for disease resistance in Sweden. These two projects have moreover developed collaboration between researchers.

Furthermore, predictions from the weather-based risk model developed in project **A10** (Börjesson et al., final report) are communicated to cereal cooperatives in order to better target analyses for mycotoxins in cereal deliveries (T. Börjesson, personal communication).

1.5.2. Current farming practices³⁹

Preventive methods

Most farmers grow cereals as part of a diverse crop rotation, and the proportion of wheat grown after wheat has decreased compared to the high frequencies observed 10-15 years ago. However, such practices are still in use. Recommendations for tillage in case of a large amount of crop residues are generally followed, and preceding crops associated with a high *Fusarium* risk are avoided. Maize is thus generally not grown in rotation with cereals, and there is no indication that this situation would change in the short term. Other preceding crops to cereals such as faba bean, with increasing interest, and winter oilseed rape are often used in practice.

Differences in variety susceptibility to *Fusarium* are not perceived as large enough to encourage most farmers' choice of variety based on this criterion. Many new varieties are registered for the Swedish markets every year, but little information on their susceptibility to *Fusarium* is communicated. This is particularly true for winter wheat. For malting barley, there is little attention given to *Fusarium* susceptibility, unless large disease outbreaks are seen in previous years.

Most farmers (up to 95 %, A. Adholm, personal communication) buy seed from Lantmännen, which guarantees clean, thermo-treated seeds. Other seed producers (e.g., Svenska Foder AB, self-produced seeds) do not provide such guarantees.

Chemical control

Unless a strong pressure was observed in the previous year, farmers base their fungicide control on regional warnings from the PPA, which compiles risks based on weather at the regional scale. When a high risk based on weather conditions is found, farmers are advised to spray in fields presenting high risks according to the general Jordbruksverket recommendations to minimize *Fusarium*-derived toxins in cereals⁴⁰. The PPA does not currently aim at providing direct warnings at a smaller scale. Fungicide treatments against *Fusarium* are not systematic, and are typically rare in some regions (e.g., Östergötland). The blooming period is however difficult to define, so that treatments are not always well timed. Farmers/advisors can also contract the DSS ProPlant developed by Bayer (Germany), which provides a treatment decision tool at a regional scale, although its use in Sweden seems to be rare. The fungicide Proline is the favoured chemical against *Fusarium*, as it is the cheaper and often already available option as it is used by most conventional farmers to fight other fungi throughout the season.

³⁹ Data presented here are based on interviews with five field advisors in cereals in Sweden: B. Roland (HS), A. Adholm (HS), A. Sjöberg (Lovang lantbrukskonsult), L. Johansson (Jordbruksverket), and K. Holstmark (Jordbruksverket).

⁴⁰ Recommendations to minimize *Fusarium* toxins DON and ZEA in cereals [original title: Rekommendationer för att minimera fusariumtoxinererna DON och ZEA i spannmål]. Annual publication from Jordbruksverket

The low proportion of oat fields treated by chemicals in 2010 can be explained by the fact that oats was then considered as a low-problematic crop, for which chemical treatments were not needed. Since then, problems have arisen with FHB and DON-contamination, and Proline has been registered in oats, so that the picture may have changed today. However, the timing of treatment in oats is difficult, as the flowering period is not easily detected in the field, which can prevent some farmers from spraying.

1.5.3. Field trials and advisory services

Some projects have been done in close collaboration with the national field trials. For example, routine variety trials for *Fusarium* resistance were initiated by project **A3** (Börjesson, final report). The publications of results in the annual reports of the national field trials were first published in 2016 for winter- and spring wheat and oats in conventional farming⁴¹. However, some methodological issues with the fungal inoculation have been faced in some locations. Analyses of variation within and across fields are furthermore lacking from field trial reports. Additionally, an investigation on the optimization of timing for fungicide application (i.e., flowering period, Sixtensson, personal communication) has been done in collaboration between the national field trials and project **A10** (Börjesson et al., final report). A collaboration with the PPA is ongoing to complement the weather-based risk index developed in project **A10** (Börjesson et al., *Id.*) with agronomic factors. The weather-based risk index is currently used by the PPA to compile risks at the regional scale in order to provide regional warnings to farmers. Farmers then adapt their control strategies based on the risk of *Fusarium* infection at the field scale published by the PPA³⁹. The PPA does not currently aim at giving direct warnings to farmers at a smaller scale.

The researchers involved in funded projects have been involved in revisions of the recommendations from Jordbruksverket, which have been updated yearly to include results from projects. Jordbruksverket recommendations cover the areas of available knowledge from prevention to control, accounting for both abiotic (weather and region) and biotic (variety) factors, although they do not provide detailed information on e.g., risk associated according to a given volume of precipitation, or to other preceding crops to cereals used in practice (faba beans, oilseed rape).

1.6. Discussion

The ten IPM projects targeting FHB and the production of mycotoxins in cereals, funded by Stiftelsen Lantbruksforskning and Jordbruksverket during the period 2009-2014 with a total budget of 16.11 MSEK, largely dealt with fungal biology, risk assessment, and techniques for resistance breeding. The development of methods and set-up of variety field trials were also important foci of the funded projects. A model predicting DON-content in oats was partially developed, and an alternative control measure to conventional fungicide was brought forward with the potential treatment of crop residues with an antagonistic fungus. The risk of infection initiated by contaminated seed material was highlighted. All projects did not result in a fully developed product and most are still at the research stage. Changes in climate and cultural practices could increase maize production in Sweden, in which case the risk for FHB problems might increase. Crop rotation that includes maize as preceding crop for cereals, particularly when a large amount of crop residues is left in the field and low-tillage techniques used, present a risk for FHB. The presence of sexual reproduction of *Fusarium* in Sweden additionally suggests that the production of spores from residues can occur from crop residues even after two years so that crop rotation and tillage regime should be chosen accordingly.

The recommendations given by Jordbruksverket to limit risk of DON-contamination cover the current state of knowledge, and are similar to those given elsewhere (e.g., France⁴²), although more details are found in the latter. However, implementation of such recommendations is not always found in practice, with for example the cultivation of wheat

⁴¹ Field trials reports for Skåne [original title: Skåneförsök] (Sverigeförsöken 2016)

⁴² Regional fungicide strategies [original title: Stratégies fongicides régionales] (Arvalis, 2016)

after wheat that can still be observed by advisors. The use of clean (e.g., thermo-treated) seeds could additionally be recommended according to results from project **A11**. This is, however, already found in practice for a majority of seeds sold to farmers.

Variety trials for *Fusarium* resistance have been implemented in the national field trials, as a result of project **A3**. However, some methodological challenges have been faced regarding fungal inoculation in 2016. Analyses of the trials are currently limited to variety differences at a single location without data on variability within treatments, and no overall analyses (over year and locations) have been provided both in the research project and in the first trial.

The model predicting DON-content in oats is still in development in collaboration with Denmark and Norway (the EU-interregional programme ÖKS), and a collaboration with Jordbruksverket advisory services is ongoing to complement the weather-based risk index with agronomic factors.

Finally, no biopesticides are currently registered in Sweden against *Fusarium*, although available in some foreign markets. Project **M2b** pointed out the difficulties in testing these products due to (1) reticence from the companies developing these products to have them tested without their control and (2) lack of funding for multi-year field studies.

1.7. Conclusion

The results from the IPM projects targeting FHB confirm that *Fusarium* infection in cereals is stimulated by several factors such as an initial presence of inoculum and favourable weather conditions, namely rain and wet environment around the crop blooming period. Moreover, the results also show that good cultural practices such as a wise crop rotation and tillage regime can reduce the risk of *Fusarium* development over the season. In addition, the ongoing development of *Fusarium*-resistant varieties holds promise for decreasing the risk for FHB and therefore reduces the need for chemical treatments in the future. Chemical treatments against FHB are generally based on regional weather-based risk assessment that farmers adapt based on their risk level compiled with some agronomic features. Most advances of Swedish research have been communicated to advisory services, have initiated new research projects, or are used by the industry. However, a few weaknesses were pointed out:

- 1) No breakthroughs in *Fusarium*-management tools to reduce DON-contamination have come forward and even though clear advances have been made many questions remain unanswered.
- 2) High variation in the analyses of DON-levels is found within fields and among plant heads so that samples taken might not always be representative of DON-contamination.
- 3) Many projects have focused on *Fusarium* pressure, whereas the relationship between *Fusarium* pressure and mycotoxin production is not clear
- 4) Methodology and analyses used in the variety trials aiming at testing resistance properties need improvements to provide clear recommendations to farmers. So far, the fungal inoculation has faced methodological problems and no analyses of variation have been provided either as results of research projects or from the national field trials.
- 5) Further development of the localised DSS (project **A10**) and the development of user-friendly interface could improve local *Fusarium* management based on predictions at a field/farm scale. Such DSS would benefit from a better understanding of the mechanism of mycotoxin production and an early detection of *Fusarium* in the field. The aim of an ongoing project⁴³ is to develop a DSS accounting for the latter. The project is part of the EU-Interregional programme ÖKS (Öresund-Kattegatt-Skagerrak) and done in collaboration with Denmark and

⁴³ Innovation for sustainable plant production [original title: Innovationer för hållbar växtodling], co-financed by Västra Götaland region and Lantmännen Research Foundation.

Norway. The development of early detection methods, such as the spore traps on leaves currently investigated in project O-16-20-767 (SLU) might improve such predictions in the future. Additionally, development and commercialization of *Fusarium*-resistant varieties could decrease *Fusarium* pressure in the future. Such development is currently ongoing, with the financing of project O-15-20-346 (Lantmännen).

- 6) *Fusarium* and derived mycotoxin production is a global issue so that up-to-date, international visibility on the topic and measures taken elsewhere would be valuable. This particularly calls for international collaboration of the research.

Through this work, additional needs in R&D could be identified (Box 16).

Box 16: Integrated Management of *Fusarium*: Knowledge gaps identified in this report

Prevention

- The mechanisms under mycotoxin production as well as the impact of fungicide treatments on mycotoxin production are not fully understood, and could shed light on the lower or equal mycotoxin contamination observed in organic compared to conventional systems in Northern Europe (Brodal et al. 2016)
- A better mechanistic understanding of *Fusarium* attacks at the field scale could improve the precision of chemical treatments and/or lead to selected harvest.
- All studies have focused on DON and little is known about the occurrence of other *Fusarium*-produced mycotoxins (particularly ZEA, T-2, and HT2 for which restrictions exist in the EU).

Monitoring

- There is a need for improved reliability of mycotoxin contamination measures at the field/load scale. Indeed, large, unexplained variation has been mentioned, both between laboratories carrying out the analysis, and between samples within the same load/field, which calls for the development of a sampling size/standardized procedure that would ensure a reliable measure. In addition, the accuracy of visual observation (proportion of pink kernels) to assess FHB-infection and DON-contamination would need to be measured.
- Improved precision of annual recommendations for the prevention and control of *Fusarium* could be achieved by compiling data on the effects of faba beans and winter oilseed rape as preceding crop to cereals in terms of risk for *Fusarium* pressure, as well as improving precision on the rain/humidity conditions that increase *Fusarium* pressure.
- The relative source of variation of *Fusarium* pressure or DON-content could additionally be investigated to define if some factors (such as climate, seed quality, chemical treatment, preceding crop, and tillage) can be identified as major sources of variability, both in conventional and organic production.
- A national/Scandinavian strategy for the development and implementation of DSS in cereals (targeting the entire fungal complex) would help targeting future needs for research and implementation.

Optimization of control

- No alternative control method to fungicides is currently commercialized. New development and/or adoption of alternative PPPs available to foreign markets could therefore contribute to future management strategies. For the latter,

government incentives (i.e., cost reduction⁴⁴, subsidies) might be needed to promote their registration in Sweden.

Efficacy of PPP

- Studies of the status of fungicide resistance (particularly *Proline*, for which resistance risk is characterised as middle-high in Sweden⁴⁵), and the evolution of *Fusarium* isolates due to resistance would be needed to better prevent the risk of resistance development. Availability of other fungicides might be recommended to decrease this risk.

Other

- The potential decontamination of DON-contaminated grains, particularly intended for animal consumption, which represents the major use of Swedish-grown cereals, could be further investigated (Awad et al. 2010).
- A holistic approach, taking into consideration the spectrum of cereal pests (particularly the fungal community) over the season/rotation is lacking. The development/use of monitoring tools targeting multiple-pests would benefit such studies.

In addition, a strategic program that coordinates the different efforts to reduce FHB-pressure and DON-contamination in cereals could strengthen Swedish research in the area. Farmer involvement in such a program could further improve the implementation of research results in the future.

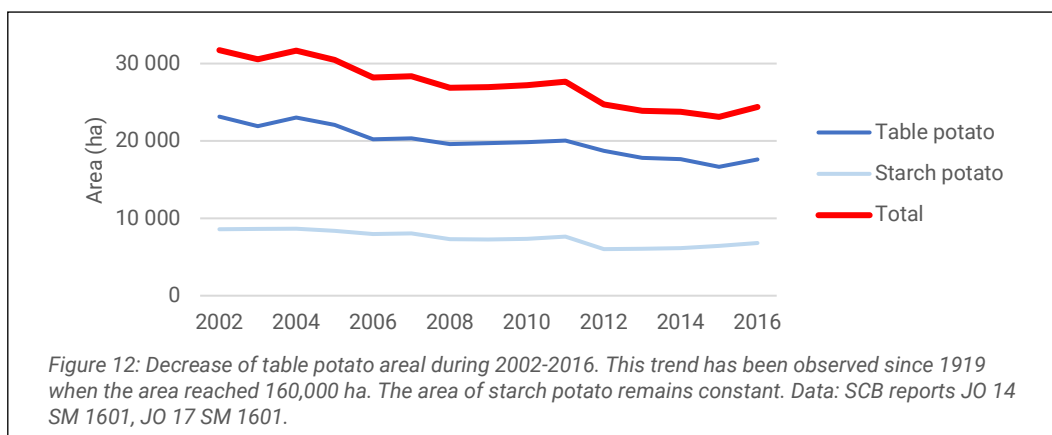
2. Phytophthora disease in potato

Phytophthora infestans, an oomycete (organism related to algae and often associated to fungi), represents a major threat to potato cultivation in Sweden. It causes late blight and tuber blight of potato and can hence reduce yields both quantitatively and qualitatively (Wiik 2014). Once contaminated, tuber blight can also develop during storage of table potato. Its prevention and control largely relies on fungicide treatments, with approximately 20 % of the total amount of fungicides used in the Swedish agricultural sector used against late blight in potatoes (Eriksson et al. 2016), although potatoes are grown only on about 1 % of the cultivated area with a tendency for potato cultivation to decrease (23,109 ha out of 2,590,100 ha in 2015⁴⁶, Figure 12). Fungicide treatments are generally applied weekly during the growing season (Wiik, Rosenqvist and Liljeroth manuscript, project C6). Concomitant with an intense fungicide use, a decrease of pesticide efficacy against *P. infestans* has been observed in recent years, and earlier attacks are observed (Wiik et al. manuscript and references therein) in Sweden.

⁴⁴ Registration costs for alternative PPPs (organic, inorganic, and biopesticides) are currently aligned to those for synthetic pesticides and therefore high compared to the size of the market

⁴⁵ Resistance, herbicide resistance, fungicide resistance, insecticide resistance [original title: Resistens, herbicidresistens, fungicidresistens, insekticidresistens] Report No. OVR292 (Jordbruksverket 2016).

⁴⁶ Report JO 10 SM 1601 (SCB 2016)



Late blight causes early wilting of potato leaves, thus reducing the energy transfer and storage in tubers. Late blight spores can also infect the tubers and cause tuber blight. A small attack on leaves can be enough to lose the entire tuber harvest in some years. Late blight has two different mating types, A1 and A2. If only one mating type occurs, reproduction is asexual, and late blight overwinters as mycelium in tubers in storage before amplification of clones of initial infection during the growing season. If both mating types occur in on the same potato leaf, reproduction is sexual with the formation of oospores, which can overwinter in the soil for a few years and enable soilborne infection of tubers. In Scandinavia, both mating types are found in equal proportions, and oospores are common and can function as primary inoculum (Sjöholm 2012 and references therein). The sexual reproduction induces high genetic variation of the pathogen, a phenomenon found at higher rates in Scandinavia compared to most other potato-growing areas (Sjöholm 2012 and references therein). There have been few problems with tuber blight in the past years⁴⁷. Starch potato has a relatively high level of potato late/tuber blight resistance in comparison to table potato, which is generally more susceptible but with varying resistance levels (susceptible to moderately resistant).

Jordbruksverket recommends both preventive and control methods to manage potato late blight⁴⁸. As preventive measures, they recommend growing potatoes in a well-drained and well-open field, no more often than every four to five years, and to use certified tubers, clean of disease, and less susceptible varieties. Weed control throughout the crop rotation is important to prevent pathogen development and survival on alternative hosts such as *Solanum physalifolium*. These recommendations are similar to those given for organic farming⁴⁹, although the length of the rotation is extended to five to six years between two potato cultivations in a same field, and the use of late blight-resistant varieties certified for organic production are recommended in organic production. Direct control only relies on fungicide treatments that are generally recommended at an interval of seven to ten days, following regional forecasts. Recommended dose is generally the same for both table and starch potato (exception for Infinito⁵⁰). The registered fungicides against late blight are shown in Table 4.

⁴⁷ Field trials reports for Skåne [original title: Skåneförsök] (Wiik et al. in Sverigeförsöken 2015)

⁴⁸ Recommendations for control of fungi and insects [original title: Bekämpningsrekommendationer, svampar och insekter] p.56 (Jordbruksverket 2016).

⁴⁹ Start organic potatoes [original title: Starta eko-potatis] (Holstmark 2015) p.3–4. Jordbruksverket.

⁵⁰ Recommendations for control of fungi and insects [original title: Bekämpningsrekommendationer, svampar och insekter] p.57 (Jordbruksverket 2016)

Table 4: Registered fungicides against late blight in potato cultivation in 2016 and additional authorized use in Swedish crop production. In **bold**: most sold substances over the past years in Sweden. Source: Keml database (2017).

Commercial appellation	Active substances [% w/w: mass fraction (% mass/mass)]	Registration in other crops
Acrobat WG	Dimethomorph 9%w/w, Mancozeb 60%w/w	onion and garlic
Banjo Forte	Dimethomorph 200 g/l, Fluazinam 200 g/l	
Cymbal 45	Cymoxanil 45%w/w	
Epok 600 EC	Fluazinam 400 g/l, Metalaxyl-M 193,6 g/l	
INFINITO	Propamocarb (hydrochloride) 625 g/l, Fluopicolide 62,5 g/l	
Leimay	Amisulbrom 200 g/l	
Ranman Top	Cyazofamid 160 g/l	
Revus Top	Difenoconazole 250 g/l, Mandipropamid 250 g/l	
Revus	Mandipropamid 250 g/l	salad and indoor tomato production
Signal	Fluazinam 500 g/l	
Shirlan	Fluazinam 500 g/l	onion

The use of DSS is recommended by Jordbruksverket to optimize fungicide treatments. Skimmelstyring (developed by Aarhus University, Denmark), VIPS (developed by the Norwegian Institute of Bioeconomy Research, NIBIO), and the commercial DSS DACOM (developed and marketed by Dacom BV, The Netherlands) are available in Sweden. Simulations from the DSS Skimmelstyring and VIPS for locations surrounding 25 weather stations in Sweden are currently tested by Jordbruksverket and currently made available from its website⁵¹. Both DSS are based on a combination of historical and current weather data and recommend dose reduction at a fixed interval (Skimmelstyring) or optimal intervals between treatments (VIPS).

Fungicide treatments of late blight has a high cost for farmers, with an average annual cost of 3570 SEK (397€)/ha in relatively resistant starch potato cultivation (Eriksson et al. 2016) and may reach up to 750€/ha in The Netherlands (Wiik et al. manuscript).

2.1. Research projects funded by Stiftelsen Lantbruksforskning and Jordbruksverket

A total of eight projects targeting IPM against *P. infestans* in potatoes have been granted during the period 2009–2016, for a total of 9.21 MSEK. These projects focused on diverse aspects of IPM of late blight, including prevention (oomycete biology, resistance breeding, variety trials), monitoring methods (suitability of DSS) and optimized control methods including alternative control methods (Table 5). The economic consideration of the use of resistant varieties against late blight was studied in project **N1**. One project (**A15**) was aimed at developing tools for detecting airborne pathogens, such as *P. infestans*, in spore traps, but the focus was changed to the detection of real fungi in cereal fields. The oomycete was therefore not further investigated in the project although the technique could be adapted to its detection in the future.

⁵¹ <http://gefionau.dk/ProjectNET/PotatoLateBlightToolbox/Show/SkimmelstyringSE.aspx?width=800&height=225>

Table 5: Research projects dealing with integrated management of *Phytophthora* in potatoes funded by Stiftelsen Lantbruksforskning and Jordbruksverket in the period 2009–2014. Additional funded applications within a research project are mentioned [italicized, in grey] in the table.

	#	Title (Institution)	Research category	Budget MSEK	(Call) Final
Prevention	(C3)	<i>Relative importance of different primary inoculum sources of <i>Phytophthora infestans</i> (SLU, project number 9942007)</i>	Biology	0.44	(1999) 2003
	(C3)	<i>Epidemiology of potato late blight (SLU, project number S0649005)</i>	Biology	1.10	(2006) 2014
	C3	Genetic diversity and aggressiveness of <i>Phytophthora infestans</i> in potato haulm and potato tubers (SLU)	Biology	1.59	(2009) 2014
	(C1)	<i>Potato breeding with emphasis on resistance to potato late blight and brown rot (SLU, project number S0636008)</i>	Breeding	5.10	(2006) 2011
	C1	Breeding of late blight resistant table potatoes for the whole of Sweden (SLU)	Breeding	2.00	(2013) 2016
	(C1)	<i>Development of late blight resistant ware potato varieties for most parts of Sweden (SLU, project number O-15-20-557)</i>	Breeding	1.90	(2015) ongoing
Monitoring	A15	Prediction of plant diseases based on molecular methods and spore traps (SLU)	Method detection	2.13	(2012) 2016
Optimization	C11	Optimized control of potato late blight (HS)	DSS	0.50	(2010) 2011
	C12	Potato late blight forecast on the web / mobile phone (HS)	DSS	0.18	(2011) 2012
	C5	Field studies for sustainable control of potato late blight – cultivar resistance and induced resistance with phosphite can reduce the need for fungicides (SLU)	Field trials / Alternative Control	2.55	(2011) 2016
	C6	Economic considerations in the control of potato late blight and tuber blight (HS)	Economic	0.18	(2013) 2013
	N1	What is the cost of prevention in plant protection? (HS)	Economic	0.08	(2013) 2013

2.2. Advances in Swedish research

2.2.1. Prevention

Biology

Andersson and Yuen (project **C3**) investigated how the infection by *P. infestans* is transmitted from infected blast to the tubers. They further studied the pathogen's genetic diversity in Swedish potato fields to better understand the aggressiveness of late blight, which has an impact on pathogen prevention and control.

Sjöholm (project **C3**, 2012, Chap. II) showed that *P. infestans* populations from infested tubers (i.e., from asexual reproduction) do not start the epidemics of late blight in Sweden and are only found three weeks after the first pathogen observation. Instead, genotypes that originate from sexual reproduction trigger the epidemics. Both soil-overwintering oospores and air-borne sporangia from surrounding fields can cause the epidemics, the latter being more probable. This implies that the pathogen can evolve rapidly, which increases the risk for circumvention of the resistance that has been developed through variety breeding. Such knowledge could impact the recommendations to farmers in terms of field management, with for example recommended distance between potato fields. The role of multiple

pathogen sources (infected tubers, oospores in soils and airborne sporangia) in pathogen epidemics is unknown.

Resistant varieties

Breeding for resistance

The only Swedish potato breeding programme has been co-financed by Stiftelsen Lantbruksforskning since 2006. This programme, based at SLU, was established when the Swedish breeding company Svalöf Weibull AB, then funded by both public and private funds, terminated its programme for the Swedish market. No other large potato breeding company has invested in potato breeding in Sweden since then. This is most likely explained by the small size of the market (Eriksson et al. 2016). Potato consumption, however, largely relies on regional production (~90 % of Swedish production is consumed domestically⁵²). Thus, suitable varieties for the region are essential for Swedish farmers and the Swedish market. Project **C1** aimed at developing the Swedish breeding program, both quantitatively and qualitatively, with a focus on late blight resistance. Particularly, an upscaling of the programme with the production of 10,000 first field year clones (i.e., tubers from different seedlings) in comparison to 3,000 achieved earlier, as well as a change in methodology, from traditional breeding techniques to the use of molecular methods, were needed to increase the chance of successfully developing new cultivars.

A modernization and upscaling of the Swedish plant breeding programme has been implemented according to plan, with both the achievement of the defined goal of 10,000 first field year clones (F1) in 2014 and 2015 (project **C1**, Carlson-Nilsson and Andreasson, final report), and the development and use of molecular markers for late blight resistance in the breeding programme (project **C1**, Lenman et al. 2016). Since the initial crossing realized in 2009, 11 genotypes were selected for the fifth-year field trial (2015) and led to the selection of six promising lines for the sixth-year field trial (2016). All lines are descendant of clone SW93-1015 which shows good resistance for late blight and for which molecular markers for resistance have been developed (Lenman et al., 2016). Of these, one line (reference 0910106) was particularly interesting with good yield, late blight resistance and good tuber qualities in both organic and conventional farming.

An overview of the situation of the potato breeding programme in the Fennoscandian region was published (project **C1**, Eriksson et al. 2016). This region is characterized by specific geographic and climatic conditions that result in special conditions for potato production. Particularly, the long day length during summer, the short growing season, and the climatic conditions are particularly suitable for late blight infection. Furthermore, a specific late blight pressure characterizes this growing region. Late blight resistance is therefore one of the main targets for variety selection, among other traits related to early maturity, yields, consumer preferences, and, for organic production, high nutrient-use efficiency. However, most of the potato cultivars grown in Sweden are currently selected and imported from outside the Fennoscandian region (particularly Denmark and The Netherlands), and most of the cultivars presently used in conventional farming are susceptible to late blight. Their cultivation therefore relies on intensive fungicide treatments. In Sweden, the current potato breeding programme has a particular focus on late blight resistance, with the use and development of molecular markers for late blight resistance (Lenman et al. 2016). Norway has had more focus on resistance against silver scurf fungal disease caused by *Helminthosporium solani* (Eriksson et al. 2016).

According to Eriksson et al. (project **C1**, 2016) the availability of suitable varieties, and particularly of varieties resistant to late blight, could increase the potato growing area in Sweden. This, together with the fact that potatoes show the highest yield per hectare of all agricultural crops in Sweden, would contribute to improving Swedish food self-sufficiency and eventually also lead to more exportation. The availability of resistant varieties would, in addition, decrease potato farmers' reliance on fungicides and therefore reduce pesticide use

⁵² Do we export Swedish potatoes? [original title: Exporterar vi svensk potatis?] (GT expressen, September 2, 2010)

in Sweden. It has been estimated that this might reduce costs with as much as 3,570 SEK/ha/year (without accounting for the environmental impact of fungicides). Eriksson et al. (2016) estimate a high potential return investment rate of such a breeding programme, and the positive impact an increased profitability could have on the potato sector in terms of employment opportunities. They therefore advocate for long-term, public investment in potato breeding programmes and 'a coordination of the breeding activities' in the Fennoscandian region. They suggest that such collaboration would be more valuable than collaboration with private breeding enterprises. Such public-private collaboration, however, has both pros and cons, namely with the potential to increase efficiency of the breeding programmes and to create litigation for rights on breeding material. Regarding collaboration within the Fennoscandian region, Norway (non-EU member state) has a two-year quarantine policy for all plant material such as potato tubers (with an exception for seeds and in-vitro cultivated tissues), which should be considered in such a collaboration. Collaboration with a private breeding company is discussed to further improve the programme (Carlson-Nilsson and Andreasson, final report).

The breeding programme is still running and has received new financing from Stiftelsen Lantbruksforskning in 2015 (project O-15-20-557, Table 5), with the goal to further develop the programme and produce offspring with combined resistance characteristics from clone SW93-1015 and from another resistant variety, Sarpö Mira, which has a different resistance mechanism. Such a cross would prevent, or postpone, the established resistance from being quickly overcome by the pathogen.

Economic consideration

Adholm et al. (project **N1**, final report) highlighted that an increase in seed price of resistant varieties might not necessarily be covered by the cost reduction in fungicide use. A yield increase would therefore be needed to reach similar incomes. However, this project is based on a small sample size and no analyses were done to support the trends, so that no conclusion can be drawn.

2.2.2. Optimization of control

Decision support system

Stadig et al. (project **C11**, final report) aimed at improving late blight control strategies in potatoes using the DSS DACOM, then the only DSS available in Sweden. They deduced issues and opportunities for the adoption of the DSS by 27 potato growers that were part of the project. DACOM is a commercial DSS developed and marketed by Dacom BV (The Netherlands) that is based on weather data from a local weather station (provided for subscribers) and weekly manual entries of plant height, growth, stage of development and potato land coverage. It informs the user about the optimum time to spray (without fixed interval) and the type of fungicide to use⁵³. All information provided by the programme can be shared between farmers and advisors (at an additional cost).

Stadig et al. (project **C11**, *Id.*) claimed that most farmers were content using the DSS, and would recommend its use in the future. A better programme interface, price, and improvement in terms of the area covered by the recommendation are suggested improvements that would benefit growers. They also mention that farmers' experience was in general used as a complement to the recommendation, before making the decision to spray. There are no clear results in terms of disease control or decrease in number of treatments and amount of fungicide used although some farmers could cover the DSS cost by a reduction of one treatment over the season. The potential use of weather data generated by the Swedish meteorological and hydrological institute (SMHI) instead of local, individual weather station was investigated by Stadig (project **C12**, final report). A comparison between the two types of weather data and respective forecast for late blight pressure was done at three locations. The forecast for late blight pressure seemed similar from two types of weather data over the season although a tendency of more warnings for strong pressure was found with local weather data. This could be related to differences in

⁵³ <http://euroblight.net/control-strategies/dss-overview/>

air humidity, which was found to be higher (+4 to 5 %) in local stations compared to SMHI data. The results of this pilot project point out the potential for the late blight forecasting model to use open weather data, but further analyses would be needed to confirm these trends.

Economic considerations in chemical treatments

Wiik and Rosenqvist (project **C6**, final report) aimed at investigating the optimal economic dose in the chemical control of late blight under field conditions and under hypothetical fluctuation scenarios of pesticide prices, and potato quality, prices, and yields. However, this pilot project has, so far, not received further funding.

Data from the national field trials on variety susceptibility and chemical treatments have been analysed for both periods 1993–1996 and 2010–2013. Wiik et al. (manuscript) showed a shift in the net economic return of chemical treatments between the two periods in table potato cultivation. In the first period, a reduction of fungicide dose (60 % of the recommended level) together with an increased interval between two treatments (average of two weeks instead of the one recommended) generated the highest net economic return. Variation in the economic returns was found according to variety resistance and pathogen pressure. Economic returns were found to be higher in susceptible cultivars than in moderately resistant cultivars (+68 % in average) and with high versus low pathogen pressure (+65 % in average). On the other hand, in the period 2010–2013 a full dose or 75 % of the recommended level showed the highest net economic return when treatments were applied once weekly. This might be explained by a decrease in fungicide efficacy due to development of resistance against the chemical agent in the period 2010–2013 (Wiik et al. manuscript). A change in the timing of *P. infestans* infections has been observed between these two periods. Attacks occurred earlier in the period 2010–2013 than in the previously studied period (-25 days on average, Wiik et al. manuscript), which suggests a change in pathogen reproduction (from asexual to sexual reproduction, see also project **C3**) with an impact on pathogen virulence. In the case of starch potatoes that generally show higher resistance to late blight, the economic net return was highest at 50 % and 25 % of the recommended dose in the period 2010–2013.

The analysis of different scenarios revealed farmers' reliance on a high potato price for high economic returns (~+40 % net return for a 40 % hypothetical increase in potato price, Wiik et al. manuscript), although an increase in net return can also be achieved with reduced fungicide doses. Fungicide price did not impact net economic return. Recommendations were therefore to decrease fungicide dose from what is recommended by producers.

Alternative control methods

Liljeroth et al. (project **C5**, 2016) investigated the effect of potassium phosphite to control potato late blight. This inorganic salt of phosphorous acid (formula: K_2HPO_3) is commonly used in some countries (i.e., Australia, Asian countries) as an inorganic PPP to control potato late blight (Kromann et al. 2012). It has been shown to both directly inhibit growth and sporulation of oomycetes (direct action) and stimulate natural defence mechanisms in the plant (indirect action) (reviewed in Kromann et al. 2012). Liljeroth et al. (2016) showed in a four-year field study that potassium phosphite has a 'good effect against [potato] late blight and tuber blight [...] under temperate conditions in Sweden'. They found that:

- The effect of potassium phosphite varies with resistance properties of table potato varieties so that more effects are found in the more resistant varieties.
- In most years, the dose response curve of both potassium phosphite and conventional fungicide treatments were similar in starch potato varieties (exception for one variety in 2011). Starch potato treated with potassium phosphite generally showed rot-free yields and starch yields as high as when treated with conventional fungicides. In addition, treatments combining both conventional fungicides and potassium phosphite at 14-day interval showed same effects than treatments conventionally realised weekly.

However, this salt is only registered as fertilizer (e.g., Proaxelin [LMI AB]), but not as a PPP in the EU. Moreover, potassium phosphite is taken up by the plant so that phosphite residues can be found in tubers. It has been shown to have a low risk to human health and environment, with a lower environmental impact (lethal dose: LD=50>5kg⁻¹, and environmental impact quotient: EIQ=8.7) than regular fungicides (e.g., Mancozeb with EIQ=25.7) (Kromann et al. 2012). The EU-regulation No 991/2014 however imposes a maximum residue levels (MRL) of phosphite and phosphate in potato at 30 mg/kg.

Regarding residues of phosphite in potato tubers, the levels observed when potassium phosphite was combined with conventional residues in Liljeroth et al.'s experiments were similar to the defined threshold (EU No 991/2014), whereas those observed when potassium phosphite was used as the sole treatment were above the MRL. This could therefore prevent implementation of the findings in practice (E. Liljeroth, personal communication). Residues in processed potato (e.g., starch and its derived products) could however contain less phosphite residues, and therefore allow the use of potassium phosphite against late blight in potatoes that are not used for direct consumption (Liljeroth, personal communication).

2.3. Additional field trials

Fungicide treatments against potato late blight have been part of the national field trials since 1998⁵⁴. The trials aimed at assessing fungicide treatment effects on yield and tuber blight infection. Since 2009, there has been only minor damage from tuber blight⁵⁵. Studies of fungicide dose reduction were part of the trials, and trials with potassium phosphite in complement to fungicide treatments have been carried out yearly since 2012⁵⁶. Since 2007, the time between all treatments has been set to seven days (before then a longer interval was also investigated). In addition, the yearly field trials aimed at testing the available DSS DACOM⁵⁷, VIPS⁵⁸ and Skimmelstyring⁵⁹. In 2016, an average of 13 % decrease in fungicide dose was observed in fields where Skimmelstyring with (with one exception) no difference in late blight damage, and the largest decrease in fungicide dose was observed when the DSS was used together with a combination of fungicide and potassium phosphite⁶⁰. Results from field trials carried out in the period 2012-2016 were summarized (Wiik et al. 2017). On average, the use of a DSS led to a 25 % reduction in fungicide use without any increase in late blight pressure. The combined use of a DSS and potassium phosphite further led to an average 40 % reduction in fungicide use (Wiik et al. 2017).

In addition, variety trials looking at late blight resistance (among other traits) are carried out yearly in organic production⁶¹. These trials are financed by Jordbruksverket (Hagman, personal communication) at a cost of 55,000 SEK/year. No variety trials are currently run for conventional varieties.

The main starch producer in Sweden Lyckeby stärkelsen has its own variety trials and results are communicated to their affiliated starch potato growers. In recent years, Lyckeby stärkelsen has communicated outputs from the DSS tested by Jordbruksverket (and available with no cost) weekly to their growers.

⁵⁴ Results from field trials on potato late blight 2007 [original title: Resultat från potatisbladmögeförsök 2007] (Wiik 2008)

⁵⁵ Field trials reports for Skåne [original title: Skåneförsök] (Wiik et al., in Sverigesförsöken 2015)

⁵⁶ *Id.* (Wiik et al., in Sverigesförsöken 2011–2017).

⁵⁷ *Id.* (Wiik et al., in Sverigesförsöken 2011–2013). Until 2012, DACOM was named PlantPlus

⁵⁸ *Id.* (Wiik et al., in Sverigesförsöken 2013–2015)

⁵⁹ *Id.* (Wiik et al., in Sverigesförsöken 2015–2017 [planned])

⁶⁰ *Id.* (Wiik et al., in Sverigesförsöken 2016)

⁶¹ Variety trials in organic production [original title: Sortval i ekologisk odling], Hagman and Halling. Annual publication

2.4. Communication

Results from the different projects have been reported through different channels. Most projects have published (two projects) or planned to publish (two projects) in peer-reviewed journals. Three of these projects additionally communicated their results in the trade press (e.g., Viola, Lyckeby stärkelsen). One project has contributed to graduate education with the publication of one PhD thesis (project **C3**). Two projects (contracted studies from Jordbruksverket) only published the final report. Means of communication are summarized in Table 6.

Table 6: Publications and communication of results [1: presence, in addition to final reports] from projects with focus on potato late blight funded by Stiftelsen Lantbruksforskning and Jordbruksverket in the period 2009–2016. In green: published and searchable publication. In orange: publication/communication channels not found online. In red: no publication/communication found.

	Popular publication		Scientific publication			Conference		Education	
	Online	Print	Peer-reviewed	Conference proceeding	Manuscript	National/regional	International	PhD	MSc
C1			1						
C3					1	1	1	1	
C5	1	1	1			1	1		
C6	1				1				
C11									
C12									

Peer-reviewed publication

- Eriksson, D., Carlson-Nilsson, U., Ortíz, R. & Andreasson, E. (2016) Overview and breeding strategies of table potato production in Sweden and the Fennoscandian region. *Potato Research* 59:279–294. [Project **C1**]
- Lenman, M., Ali, A., Mühlenbock, P., Carlson-Nilsson, U., Liljeroth, E., Champouret, N., Vleeshouwers, V.G.A.A. & Andreasson, E. (2016) Effector-driven marker development and cloning of resistance genes against *Phytophthora infestans* in potato breeding clone SW93-1015. *Theoretical and Applied Genetics* 129:105–115. [Project **C1**]
- Liljeroth, E., Lankinen, Å., Wiik, L., Burra, D.D., Alexandersson, E. & Andreasson, E. (2016) Potassium phosphite combined with reduced doses of fungicides provides efficient protection against potato late blight in large-scale field trials. *Crop Protection* 86:42–55. [Project **C5**]

Manuscript

- Wiik, L., Rosenqvist, H. & Liljeroth, E. (manuscript) Biological and economic considerations in the control of potato late blight and potato tuber blight. [Project **C6**]

PhD thesis

- Sjöholm, L. (2012) How sexual reproduction affects the population biology of *Phytophthora infestans*. PhD thesis, SLU (Uppsala, Sweden). Chap. II: Immigration and persistence of *Phytophthora infestans* in a single field. [Project **C3**]

Final reports

- Adholm, A., Nätterlund, H., Petersson, P. (2013) Vad kostar förebyggande åtgärder inom växtskyddet? Final report for Jordbruksverket 10498. [Project **N1**]
- Andersson, B. & Yuen, J. (2014) Genetisk diversitet och aggressivitet hos *Phytophthora infestans* i potatisblast och potatisknölar. Final report for Stiftelsen Lantbruksforskning H0942155. [Project **C3**]
- Carlson-Nilsson, U. & Andreasson, E. (2016) Framtagning av bladmögelresistenta matpotatissorter för hela Sverige. Final report for Stiftelsen Lantbruksforskning number H1342236. [Project **C1**]
- Liljeroth (2016) Alternativa bekämpningsmetoder mot potatisbladmögel – sortens resistens och inducerad resistens med fosfiter kan minska behovet av fungicider. Final report for Stiftelsen Lantbruksforskning H1142126. [Project **C5**]

- Stadig, H., Hedlund, K., Olsson, M., Gunnarsson, A. (201X) Optimerad bekämpning av potatisbladmögel. Final report for Jordbruksverket 4941. [Project C11]
- Stadig, H. (201X) Bladmögelprognoser på webben/mobilen. Final report for Jordbruksverket 6163. [Project C12]
- Wiik, L. & Rosenqvist, H. (2013) Ekonomiska övervägande vid bekämpning av potatisbladmögel och brunröta. Final report for Jordbruksverket number 10265. [Project C6]

2.5. Implementation

2.5.1. Industry

The potato breeding programme at SLU has received further financing from Stiftelsen Lantbruksforskning (project O-15-20-557, Table 5) to continue its work on the development of resistant varieties.

2.5.2. Current farming practices⁶²

Preventive methods

Most farmers follow a four-year rotation (usually preceded by cereals or ley), although shorter rotations, and even yearly cultivation, can still be found in some regions where potatoes are intensively grown. There is no indication that rotation is planned together with information on locally adjacent fields, to prevent potential infestation from surrounding fields.

The risk of late blight infestation from blight infested tubers is not perceived as high by farmers who generally do not account for it in their choice of seed. Tuber blight has rarely been reported as a problem in the past years by farmers growing table potatoes and by advisors, and is not a problem in starch potato production. Certified seedlings are however generally used, but mainly to prevent infection by virus or bacteria. Particularly, certified seeds are certified under a 0.2 % of bacterial soft rot, which can arise from blight infested tuber. Some farmers produce their own seedlings.

The choice of conventional farmers in terms of table potato varieties is currently not based on resistance properties but on demands from consumers or industry and production aspects. The increase in resistance threshold, i.e., the level of protection against pest pressure, is not perceived as high enough. In addition, the newly developed varieties are often not as popular/well-known among consumers and the industry in terms of internal properties. In contrast, resistant varieties are used by organic and starch potato growers. In the latter case, there are few differences in the resistance levels between different starch potato varieties, which show generally higher resistance levels than table potatoes.

Chemical control

The chemical control of late blight is part of farmers' annual fungicide plans. Treatments begin when the crop reaches row closure, and are often carried out at weekly intervals until harvest (minus withdrawal period) for table potato. Although there are no differences in treatment recommendations between table and starch potatoes, it is common to see longer intervals between treatments in starch potato production. In addition, some potato growing areas suffer less pressure than others, and intervals between treatments are often found to be longer there.

Advisor and, to a lesser extent, farmer awareness about the availability of DSSs to optimize chemical treatments against late blight seems to have increased, particularly for Skimmelstyring and VIPS that are tested and currently freely available from the Jordbruksverket website for 25 weather stations over the potato growing area. Based on a combination of historical and current weather data, these DSS recommend either dose reduction (Skimmelstyring) or longer intervals between treatments (VIPS). Although results

⁶² Data presented here are based on interviews with three advisors: A. Djurberg (Jordbruksverket), G. Olsson (Lyckeby stärkelsen), Åsa Rölin (HS) on potato cultivation in Sweden.

from DACOM were satisfactory and well suited for farmers (precise and targeted advice, based on both weather data and field growth stage), its annual cost is high and its use requires many manual inputs, which can prevent its adoption by farmers, and particularly those growing potatoes on a small scale. Close collaboration between Jordbruksverket and the research institutes developing the different DSSs have been required over the past years to enable their use in Sweden (L. Aldén, personal communication). These DSSs are still in development both generally and for adaptation to Swedish conditions so that technical issues can occur (Aldén, personal communication). All three DSSs currently used are based on local weather stations that require maintenance. However, there is an increasing indication that forecasting based on open source weather data gives similar results (Aldén, personal communication). The two DSSs were made available principally for their use in field trials, although their availability and forecasts have been communicated to advisors over the years. Lyckeby stärkelsen has included predictions of these two DSSs in their weekly letters to starch potato growers. There is, however, an indication that only a small minority of the farmers have adopted one of the three available DSSs (Skimmelstyring, VIPS or DACOM) to date.

Chemical treatments are generally not modified at the variety level according to the resistance threshold, because little data is available to farmers/advisors on the risk/benefit of such modulations.

Potassium phosphite is not currently registered as a PPP in potato cultivation. Its use as fertilizer might occur.

2.5.3. Field trials and advisory services

Some projects have been done in close collaboration with the national field trials. For instance, treatments with potassium phosphite have been included in the national field trials (project **C5**), and the use of the three DSSs was tested, each for three years with a one year overlap between two different DSSs in the period 2011–2017.

2.6. Discussion

The eight IPM projects targeting *P. infestans* and the control of late blight in potato, funded by Stiftelsen Lantbruksforskning and Jordbruksverket during the period 2009–2014 with a total budget of 9.21 MSEK, were diverse in their aims. Some dealt with organism biology under Swedish conditions, others were focused on techniques for resistance breeding, tools for forecasting, alternative and sustainable control methods, and optimized control methods (including the adoption of DSSs and the economic consideration of late blight control). These projects aimed for an implementation in potato production in both the short- and long terms.

2.6.1. Breeding for resistance

Breeding for resistance is promising in the sense that it could decrease farmers' reliance on fungicides and improve conditions for organic production. It is worth noting that the time needed to market new varieties may take years or decades. Interviews with advisors emphasized the need to improve physio-chemical properties in candidate varieties to facilitate their adoption by farmers, particularly in the case of conventional productions. Consumer preferences for some varieties might however delay farmers' adoption of new varieties.

Organic farmers are more willing to choose a less susceptible variety in view of the higher risk they face in case of high pest pressure. Indeed, late blight is the major threat to organic potato production in Sweden⁶³, which might explain the small potato acreage grown organically. Thus, an average of 5.1 % of the potato production was grown organically in 2015 with variation between type (0.10 % for starch potato and 6.8 % for table potato⁶⁴), with notably lower yields (-42.2 to -54.7 % according to years) than in conventional

⁶³ Start organic potatoes [original title: Starta eko-potatis] (Holstmark 2015) Jordbruksverket report.

⁶⁴ Reports JO 10 SM 1602 and JO 13 SM 1601 (SCB 2016)

production⁶⁵. A yearly increase of yields is, however, observed⁶⁵ (~1150t/ha; conventional farming: ~922 t/ha). Preventive measures rely mainly on the use of less susceptible varieties, longer crop rotation (5 years), and cultivation techniques (increase of row spacing and of tuber density)^{63,66}. Organic potato production would therefore benefit from the development of late blight-resistant varieties. In addition, organic production could benefit from the availability of suitable alternative control measures that can be found in other countries (Olle et al. 2015).

In Sweden, the only breeding programme for potato is run by SLU with a relatively low budget (2.1 MSEK/year for the period 2013–2018), which limits the extent to which it can develop. Its total budget is not covered by its basic funding (1.5 MSEK/year⁶⁷ from SLU and the Swedish Foundation for Strategic Environmental Research, MISTRA), and it has relied on external funds obtained from Stiftelsen Lantbruksforskning in 2013 and 2015. The programme hires two employees, one of whom works at 80 %, and has successfully reached its initial goals with the development of 10,000 new clones per year. However, the size of the programme is still well below the limit characterizing a 'small' programme (i.e., developing 15,000 clones annually), and is currently at 'the lower limit for a reasonable chance of acceptable delivery [of new commercial varieties]' (Eriksson et al. 2016). Other potato breeding programmes are generally characterized as medium, managing 15,000 to 50,000 clones annually.

2.6.2. Pest biology

New inputs on *P. infestans* biology improve the general understanding of pest life cycle and might result, in a longer term, in improved recommendations regarding farming practices such as a crop rotation accounting for surrounding fields, and/or improved forecasting and control.

2.6.3. Optimized and alternative control methods

The results from the economic analysis of chemical control could potentially give farmers economic incentives to reduce fungicide use. There is presently no general awareness of this option among potato farmers.

Results from field trials show that the three DSSs available on the Swedish market have the potential to guide potato growers in a reduction of fungicide dose. All three DSSs have been tested in field trials each for three years, ending in 2017 (with one year overlap between two different DSSs). Availability of DSSs and results from field trials have mainly been communicated to advisors. Receptivity from advisors and farmers has improved in the past years, but their adoption is currently rare. The cost inherent to the DSS is currently paid by Jordbruksverket during the test period that ends in 2017. Uncertainties about the situation in the future (choice of DSS, costs, whether Jordbruksverket should support those costs) remain. VIPS in Norway and Skimmelstyring in Denmark are freely available to growers. VIPS is also available as a smartphone application.

Finally, the results from the projects confirm the potential of potassium phosphite as complement to chemical control. However, this finding faces regulation barriers as (1) potassium phosphite is not registered as a fungicide agent at the EU-level and (2) its future registration might be compromised by a new EU-regulation imposing a threshold in the amount of phosphite residues authorized in potatoes. Implementation of these results would therefore require additional trials to lower phosphite residues in potatoes (e.g., by avoiding late treatments with potassium phosphite) and research on phosphite residues in transformed products such as starch. If results are satisfactory, discussion between researchers, industry, and responsible authorities would be needed to register potassium phosphite as a PPP in the EU and Sweden. The cost of such registration might, however,

⁶⁵ Report JO 14 SM 1601 (SCB 2016)

⁶⁶ Organic cultivation of table potatoes [original title: Ekologisk odling av matpotatis] (Jordbruksverket 2003).

⁶⁷ This budget does not account for in kind from professors E. Andreasson and R. Ortiz (SLU)

prevent incentives from industry to register the product because of its simplicity and low cost to produce, and the impossibility to patent it.

2.7. Conclusion

The studies presented here have supported the assertion that a specific late blight pressure is found in Sweden due to the presence of both mating types allowing sexual reproduction and to favourable seasonal conditions. Late blight attacks are initiated by the presence of inoculum (contaminated tubers, soilborne oospores, or air-borne sporangia) and favourable wet conditions. The prevention of late blight attacks mainly relies on crop rotation and the use of resistant varieties and certified seedlings. Advances in Swedish research have highlighted the potential risk of contamination between fields, from movement of air-borne sporangia. This underlines the need to account for surrounding fields in rotation planning, as recommended elsewhere⁶⁸.

Advances in Swedish research suggest that it is possible to reduce fungicide dose as a result of increased variety resistance, without a decrease in net economic return. The potential of potassium phosphite as complement to fungicide treatments has also been reported, with its potential to decrease the dose and lengthen the interval between treatments. Implementation of these findings is, however, compromised by a EU-regulation on the level of authorized phosphite residues in potatoes. There is, so far, no recommendation for adjusting fungicide dose according to the level of innate resistance threshold of potato varieties (and particularly for starch potatoes that generally show higher resistance levels compared to table potatoes) by Jordbruksverket although there is evidence that this is possible without reduction of yield and this may even improve net economic return. However, the farmers' cooperative and leading starch potato company Lyckeby stärkelsen has adopted the goal to reduce the use of fungicides in starch potato production to 50 % before 2020 compared to the 2014-level (J. Biärsjö, personal communication). Trials and communication of table potato varieties' resistance levels (except for organic production) seem to be lacking.

The adoption of one of the three DSSs available in Sweden is not widespread among farmers although it shows the potential to decrease the frequency and/or dose of fungicide used against late blight. Additionally, the future availability and conditions of use (particularly cost) of the DSSs are uncertain, as is also its impact on fungicide resistance.

Most advances of Swedish research have been communicated to advisory services and good collaborations are observed between researchers and advisory services, breeding programmes, and industry. Most projects have further initiated new research projects, or are used in the national breeding programme. However, a few weaknesses may be pointed out: (1) Data on resistance of potato varieties available for the Swedish market are lacking (2) The total budget of the Swedish national potato breeding programme (including both basic financing from SLU and Mistra and additional Stiftelsen Lantbruksforskning funding) is limited, covering salaries for two employees and operating costs to reach the minimum size for potential variety development. Additional contributions to the core financing, for instance through collaboration with private breeding companies or other national programmes, might increase its size and, with it, its chance to deliver new varieties for the Swedish market.

Through this work, additional needs in R&D could be highlighted (Box 17).

⁶⁸ Cultivate field potatoes in organic farming [original title: Cultiver la pomme de terre de plein champs en agriculture biologique] (Technical Institute for Organic Agriculture, ITAB 2011).

Box 17: Integrated Management of *Phytophthora*: Knowledge gaps identified in this report

Prevention

- There is limited knowledge about the factors affecting tuber blight pressure. Particularly, there is no measure of the effect of preventive spraying done later in the potato growing season against late blight control on tuber blight and *P. infestans* population dynamics. The absence of problems due to tuber blight in the past years might be due to an increased resistance in potato varieties, which could indicate potential to reduce fungicide use later in the season.
- Continuous development of new resistant varieties, suited for Swedish conditions and that show good internal properties and yields would benefit growers (including organic growers), with the condition that seed prices are set so that the use of less-susceptible varieties is economically sound for farmers. Additional funding to the Swedish potato breeding programme (project **C3**) has been granted in this sense in 2015 (O-15-20-336). In addition, the study of the potential of cisgenesis of genes conferring resistance properties in potato varieties is furthermore undertaken in a MISTRA-funded project.
- Additionally, a focus on improving yields in regions presenting low late blight pressure might encourage farmers to grow more potatoes in these areas.
- There is a need for variety trials in terms of resistance to late blight which, together with more evaluation and better communication of economic returns in fungicide trials according to varieties' resistance levels, could provide more incentive to farmers to reduce fungicide dose.

Monitoring

- Research aiming at improving late blight monitoring, such as with the use of spore traps (see e.g., in cereals: project **A15** and follow-up) could improve local prognosis at early fungal infection stage.

Optimization of control

- The development of DSSs at the field scale, based on up-to-date research results (including variety resistance characteristics) and its availability in a friendly and affordable interface to advisors and farmers would help individual farmers to implement IPM and reduce fungicide use. There is particularly an unexplored potential to use open-access weather data as inputs for forecasting models. This could compete with the need to develop local weather stations and decrease forecasting costs. This goes together with a need for good internet access that covers rural areas. A strategic agenda for the implementation of DSSs in Sweden would be needed to secure development and adoption among the farmers.
- The promising reduction of fungicides obtained with a combination of potassium phosphite would need further research to comply with the EU-regulation setting the MRL of phosphite residues in potato. Particularly, additional trials aiming at reducing phosphite residues (e.g., by avoiding late treatments with phosphite) and analysis of phosphite residues in transformed products such as starch could allow field application of phosphite under some conditions. In the case of promising results, the question around the registration of potassium phosphite as a PPP would need attention. Particularly, the cost of such registration as well as the simplicity (impossibility to patent) and low cost to produce the substance might prevent incentives from industries.
- The impact of decreased fungicide dose on development of *Phytophthora* resistance to fungicides is not known. Determination of the type of resistance and corresponding fungicide sensibility might be needed to understand resistance development (Mikaberidze et al. 2017).

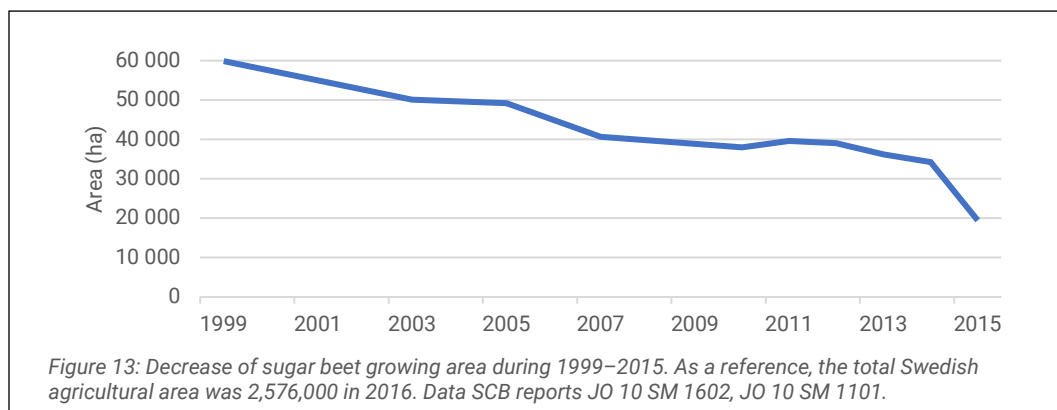
- Late blight management in organic production suffers from a lack of research, with few recommendations available to farmers. Means to identify and locate sources of late blight infections is currently investigated in a newly funded Stiftelsen Lantbruksforskning project⁶⁹.
- Little attention has so far been given to the development and/or testing of alternative control methods. For example, foliar and seed mineral or biological treatments are available in other European countries (Olle et al. 2015), and might be suitable for Swedish market.

Other

- A holistic approach, taking into consideration the spectrum of potato pests over the season/rotation is lacking.
- Participatory research, involving farmers, could improve implementation of research results (e.g., variety trials, DSS) in the future.

3. Beet cyst nematodes in sugar beets

Beet cyst nematode (BCN, *Heterodera schachtii*) is one of the major threats to sugar beet cultivation in Sweden and can reduce yields both quantitatively and qualitatively with associated reduction in sugar content. Its management largely relies on preventive measures such as crop rotation and the use of resistant varieties. No chemical treatments are available against BCN. The entire sugar beet production is regulated by the European Commission with a Swedish sugar quota corresponding to 2 % of EU-total content. Sugar beets are grown on about 1 % of the Swedish cultivated area, with a reported decrease from the level observed 15 years ago (Figure 13). The decrease observed in 2015 was due to good yields achieved in 2014 so that the quotas were fulfilled. The sugar beet growing area in 2016 was back to the same level as 2014, which is around 30,000 ha (Å. Olsson, personal communication).



BCN parasitize sugar beets' roots, which limits nutrient adsorption and reduces the size of storage roots. They delay sugar beet growth, and provoke the discoloration and wilting of leaves (Lilley et al. 2005). The infection can be detected visually in the field after several weeks of parasitism, with the presence of adult female BCN (cysts) attached to sugar beets' roots (Lilley et al. 2005). In addition to sugar beets, host plants are Brassicaceae (oilseed

⁶⁹ Digital tool for identifying and locating potato late blight in organic potato cultivation [original title: Digitalt hjälpmedel för att identifiera och lokalisera bladmögel i ekologisk potatisodling] (project R-17-20-002, budget: 0.25 MSEK, Partnerskap Alnarp, 2017)

rape, cabbage, turnips, some weeds species), and Chenopodiaceae (spinach, some weeds) as well as celery and carrots⁷⁰. There is no organic sugar beet production in Sweden⁷¹.

The use of preventive methods is recommended against BCN⁷². A four-year crop rotation is advised to prevent BCN outbreaks. Oilseed rape is not recommended as part of the rotation as it is a host plant for BCN. If it is to be included; a five-year crop rotation should be planned. The use of sanitizing intercrops can be used to reduce BCN densities in the soil. Farmers are advised to control for the presence of BCN in case of suspicion of occurrence. If the presence of BCN is confirmed, it is recommended to grow tolerant varieties. Two types of varieties are available on the Swedish market according to their resistance levels to BCN:

- 1) Normal (N): variety susceptible to BCN
- 2) Nematode Tolerant (NT): variety able to limit yield suppression compared to a susceptible variety, without reducing BCN reproduction.

NBR carries out yearly testing of sugar beet varieties for BCN tolerance and yield. So far, no nematode resistant (NR) variety, defined after their ability to limit BCN reproduction, is registered in Sweden (Olsson, personal communication). The results of such field trials form the basis of yearly approval by a variety commission of NT-varieties in Sweden. The first tolerant variety to BCN was registered in 2005 in Sweden⁷³. Since then a few tolerant varieties are available to farmers. Varieties showing semi-tolerance to BCN are referred to as 'Nematode Escape' (NE) varieties.

3.1. Research projects funded by Stiftelsen Lantbruksforskning and Jordbruksverket

A total of five applications have been granted during the period 2009–2014 that targeted IPM against BCN in sugar beets, for a total budget of 3.65 MSEK (Table 7). The research projects mainly deal with BCN prevention and with risk assessment and monitoring.

Table 7: Research projects dealing with integrated management of BCN in sugar beets funded by Stiftelsen Lantbruksforskning in the period 2009–2014.

	#	Title (Institution)	Research category	Budget MSEK	(Call) Final
Prevention	D4	Testing of beet varieties on nematode infested land (NBR)	Field trials	0.39	(2009) 2010
	D5	The influence of different sugar beet varieties on population dynamics of the beet cyst nematode (NBR)	Field trials	0.34	(2010) 2012
	D1	Survival of beet cyst nematode <i>Heterodera schachtii</i> in the biogas process (SLU)	Risk assessment	0.65	(2009) 2012
Optimization	D2	Development of decision support for planning crop rotation in sugar beet production (HS)	DSS	0.85	(2010) 2013
	D3	Influence of manure and sugar beet varieties on beet cyst nematodes (HS)	DSS	1.40	(2011) 2016

3.2. Advances in Swedish research

3.2.1. Prevention

Farming practices

⁷⁰ <https://www7.inra.fr/hyppz/RAVAGEUR/6hetsch.htm>

⁷¹ Organic and conventional production - a comparison of crop areas. Agriculture in numbers [original title: Ekologisk och konventionell produktion – en jämförelse av grödarealer. Jordbruksverket i siffror] (Jordbruksverket 2016)

⁷² Cultivation guide, integrated plant protection - sugar beet [original title: Odlingsvägledning, integrerat växtskydd – sockerbetor] (Jordbruksverket 2014)

⁷³ Final report Stiftelsen Lantbruksforskning project V0644004: Remediation of beet cyst nematodes with resistant trap crops [original title: Sanering av betcystnematoder med resistent mellangrödor] (Olsson, 2010)

Omer et al. (project **D3**, final report) investigated the influence of fertilization on the development of BCN. They compared BCN development at different initial population densities in the presence of mineral fertilizer (NPK 14-4-8) or animal manure. The results did not provide consistent enough evidence to draw conclusions: no significant difference was observed between fertilization treatments although a trend of higher BCN development was observed in presence of cattle slurry at low initial BCN density.

Use of resistant varieties

Stiftelsen Lantbruksforskning has co-financed annual variety trials of sugar beet for BCN resistance in 2009, 2010, and 2011. Variety resistance in terms of yield response (projects **D4** and **D5**) and/or BCN proliferation (projects **D3** and **D5**) were investigated. In addition, Omer et al. (project **D3**, final report) and Olsson et al. (projects **D4** and **D5**, final reports) investigated the influence of sugar beet varieties on BCN population dynamics.

Olsson et al. (project **D4**, final report) tested 17 sugar beet varieties (N, NE and NT) in BCN-infested soil. They show an average increase of 14 % yield obtained with NE- and NT-varieties compared to N-varieties in BCN-infested soil. Julietta (NT) showed the highest yield increase compared to the reference variety Rasta (N) in BCN-infested soil. However, yield from NT- and NE-varieties in soil free of BCN was lower than N-varieties. This emphasized the need to assess BCN presence in the field to optimize the choice of variety.

Olsson et al. (project **D5**, final report) investigated the effect of five sugar beet varieties with different resistance levels in infested soils on quantitative (yield) and qualitative parameters on BCN population dynamics, as well as the relationship between yields and initial BCN densities, according to varieties. Both field experiments, replicated in Sweden and Denmark, and greenhouse experiments were used. Olsson et al. (*id.*) showed that yields were dependent on variety and region in BCN-infested soil although the varieties Rosalinda (NE) and Julietta (NT) ranked within the highest yielding varieties both in Sweden and Denmark. They showed that varieties impacted BCN proliferation in the field, which was on average five-fold the initial density in normal varieties, and reduced to ~3.2-fold in NE- and NT-varieties in Sweden. There was no relationship (coefficient of determination, $R^2 < 1.8\%$) between yield and initial BCN densities for any varieties in Sweden due to low initial densities. In contrast, some relationship was found in the Danish field trials that had higher initial densities, particularly for N- and NE-varieties ($R^2 \geq 60\%$). Additional field experiments showed that the NT-variety Cactus hindered cyst development and BCN development within cyst (-50 % egg and larva per cyst) on sugar beet roots at middle and high BCN densities (>0.5 juveniles/g. soil) compared to the N-variety Mixer. NE-variety Rosalinda showed reduced cyst development at high BCN density. A model for BCN population dynamics was parameterized according to sugar beet varieties. The model outputs gave the potential yield reduction in case of high initial BCN densities, which could reach up to 70 % for N-varieties although model fit was variable according to varieties (coefficient of determination: $R^2 = 3-49\%$).

Omer et al. (project **D3**, final report) aimed at further parametrizing the DSS for BCN development in different sugar beet varieties. They found a trend of increased BCN development in N-varieties compared to NE- and NT-varieties. The increase was significant one out of the three years of experiments with a 2-fold BCN population increase in N-varieties compared to NE- and NT-varieties. They observed a tendency toward a negative correlation between BCN development and initial BCN population density, with increased BCN development rates when initial BCN densities decrease. The correlation was, however, not statistically significant so that there was insufficient support to draw clear conclusions.

Risk assessment

Jakobsson and Schnürer (project **D1**, final report) examined BCN survival during the biogas process and therefore the possibility of being spread in the fields through crop residues. The data show that inactivation of BCN is not achieved during the biogas process. Indeed, the time required for a complete inactivation was not fulfilled due to the continuous biogas process with input several times a day. They observed that an increased nitrogen content

could have a positive effect on the inactivation, so that biogas processing plants using a high, but not a low, nitrogen content could kill BCN during the biogas process. This would need to be confirmed by further research to extend recommendations for the addition of nitrogen-rich material in the process of infested material. The inactivation of BCN was also achieved by sanitation (as recommended by Jordbruksverket ⁷⁴) and by a longer aerobic storage of two weeks at a minimum temperature of 10°C before spreading on fields.

3.2.2. Monitoring: DSS

Wallenhammar et al. (project **D2**, final report) developed a preliminary version of BCN-Watch, a DSS for BCN management through crop rotation planning in sugar beet production. The initial plan was to develop such a DSS based on avoiding risks of multiple pests (soilborne pathogens and nematodes) but the project has suffered from some limitations and delay due to staffing issues. Data collected on variety tolerance levels and BCN population dynamics in relation to initial BCN population density (projects **D3–D5**) was combined to predict BCN population dynamics during the sugar beet growing season and during the crop rotation, and to advise on the choice of suitable variety. Effect of resistant trap crops on BCN populations (determined in Stiftelsen Lantbruksforskning project V0644004⁷⁵) was also accounted for in the model. The predictions indicate that, if conditions of initial population densities, variety, and preceding crops are met, sugar beets could be grown every three years. A next step would be to evaluate model predictions with field data. Further developments are needed to provide a web-based DSS. A preliminary version (not web-based) is downloadable from HS website⁷⁶.

3.3. Additional field trials

Annual field trials (including variety trials in terms of BCN tolerance) are carried out by NBR and communicated through their channels to sugar beet growers, and on their website⁷⁷. The base financing of the national field trials does not include the financing of sugar beet variety trials. Thus, the financial contribution from Stiftelsen Lantbruksforskning relied on successful applications to open/special calls.

3.4. Communication

Results from all projects have been published through popular channels (Betodlaren, NBR website). One project is planning a peer-reviewed publication. Means of communication (in written and oral form) are summarized in Table 8.

Table 8: Publications and communication of results [1: presence, in addition to final reports] from projects with focus on BCN funded by Stiftelsen Lantbruksforskning in the period 2009–2016. In green: published and searchable publication. In orange: publication not found online. In red: no publication/communication found.

	Popular publication			Scientific publication		Conference		Education	
	Online	Print	Peer-reviewed	Conference proceeding	Manuscript	National/regional	International	PhD	MSc/BSc
D1		1							
D2	1				1	1			
D3	1								
D4	1					1	1		
D5	1	1				1	1		

⁷⁴ Sanitation at 70°C for one hour or at 52°C for ten hours (Swedish Board of Agriculture, Anaerobic digestion of animal by-products [original title: Rötning av animaliska biprodukter], 2011-09-21).

⁷⁵ Remediation of beet cyst nematodes with resistant trap crops [original title: Sanering av betcystnematoder med resistentta mellangrödor] (1.25 MSEK, Å. Olsson, 2006–2010)

⁷⁶ <http://hushallningssallskapet.se/tjanster-produkter/trycksaker-brev/>

⁷⁷ <http://www.nordicbeet.nu/>

Final reports

- Jacobsson, K. & Schnürer, A. (2012) Överlevnad av betsystematoden *Heterodera schachtii* under biogasprocessen? Final report for Stiftelsen Lantbruksforskning H0944021. [Project **D1**]
- Olsson, R. (2010) Provning av betsorter på nematodinfekterad mark. Final report for Stiftelsen Lantbruksforskning V0944027. [Project **D4**]
- Olsson, Å. (2012) Mottaglighet och tolerans hos olika betsorter gentemot betcystnematoden *Heterodera schachtii* 2011. Final report for Stiftelsen Lantbruksforskning H1044070. [Project **D5**]
- Omer, Z., Levenfors, J., Wallenhammar A-C. (2016) Inverkan av stallgödsel och sortval på betcystnematoden Final report for Stiftelsen Lantbruksforskning H1144237. [Project **D3**]
- Wallenhammar, A-C., Levenfors, J. & Omer, Z. (2013) Utveckling av beslutsstöd för växtföljdsplanering i sockerbetsproduktionen. Final report for Stiftelsen Lantbruksforskning H1044234. [Project **D2**]

3.5. Implementation⁷⁸

3.5.1. Current farming practices

Preventive measures

The availability of soil analysis services and tolerant varieties is well established within the advisory services for sugar beets growers. Such measures are adopted by most growers who test their field for BCN, and chose sugar beet variety accordingly. The improvement of NT-varieties in terms of yields reduces the importance to optimize the variety choice at low BCN-density. However, BCN can multiply in N-and NT-varieties so that farmers are advised to carefully follow BCN-development and to act if they reach critically high levels (Olsson, personal communication). Among the ten sugar beet varieties currently available in Sweden (A. Ryden, personal communication), four show some degree of resistance against BCN. Various laboratories offer analysis of BCN in soil samples, and field mapping of BCN population densities is available from HS⁷⁹.

A four- to five-year crop rotation is, in general, well-adopted for sugar beet production to prevent BCN outbreaks. Winter oilseed rape⁸⁰ is often grown in crop rotations that include sugar beets and farmers are advised to follow the BCN densities with soil samples.

Sugar beet fields are generally fertilized using mineral fertilizers or pig slurry in areas with large pig production. Knowledge and concerns on the impact of different types of fertilizers on BCN seems not to be widespread among advisors and growers.

Decision support system

No DSS is currently known or used by advisory services or growers. The need for such a tool to plan crop rotation with a sole focus on BCN management does not seem to be important for growers and advisory services.

3.5.2. Field trials and advisory services

Annual variety trials for BCN tolerance are carried out by NBR and communicated through NBR's channels to sugar beet growers, including their website⁸¹. The development of NT-varieties has improved during recent years and these can now be grown without any yield penalty in non-infested soils.

⁷⁸ Data presented here are based on interviews with three advisors in sugar beet cultivation in Sweden: A. Bauer (HS), A. Gerdsson (Jordbruksverket), A. Ryden (Nordic Sugar).

⁷⁹ <https://odlarservice.se/>

⁸⁰ Winter oilseed rape maintains the population in the soil (no increase observed) in contrast to spring oilseed rape (Olsson, *personal communication*).

⁸¹ <http://www.nordicbeet.nu/>

3.5.3. Risk assessment: BCN-infested sugar beets used in biogas process

The use of BCN-infested sugar beets for biogas production seems very rare in Sweden. BCN-infested sugar beets can be sold to the sugar industry to a, however, lower price due to external and internal properties.

3.6. Discussion

The five IPM projects targeting BCN funded by Stiftelsen Lantbruksforskning during the period 2009–2016 with a total budget of 3.63 MSEK, have generated knowledge on preventive measures and risk assessment. BCN-development under different fertilization regimes and in sugar beets with different levels of tolerance levels was investigated. These results were compiled in a preliminary version of a DSS, BCN-watch, which aims at predicting BCN population dynamics in real conditions according to field and management data entered by the farmers. The aim of another project was to assess the risk for BCN to survive the biogas process.

Interviews with advisors highlighted that: (1) implementation of knowledge on the use of tolerant varieties when risk is shown after soil analysis is widespread, and such preventive methods is used by most farmers; (2) the need for a DSS to plan crop rotation with the aim to prevent outbreaks of BCN (such as BCN-watch) seems limited according to the advisory services and growers; (3) the use of sugar beets for biogas production is not common in Sweden, so that the relevance of the project investigating the survival of BCN in the biogas process seems limited.

There is, as yet, no distinction in Jordbruksverket recommendations between winter and spring oilseed rape although a difference in impact on BCN development is found (Olsson, personal communication)⁷⁸.

Annual variety trials on BCN-infested soils are carried out and financed by NBR and seed companies. They are not part of the base financing of national trials (carried out by HS). The methodology of such trials was developed with support from initial funding by Stiftelsen Lantbruksforskning. Recommendations on resistance properties according to risk levels are well-followed by farmers.

3.7. Conclusion

BCN management is special in the sense that it only relies on preventative measures, as there are no available direct control methods. The prevention of BCN damage mainly relies on crop rotation and the use of tolerant varieties. No completely resistant varieties are currently registered in Sweden or in other European countries as their yield levels are not satisfactory. Advances in Swedish research showed the differences in yield and resistance levels according to initial BCN densities and varieties. Initial population assessment at the field scale is therefore needed, and generally observed in the field, to optimize variety choices and subsequent yields. Variety properties in terms of resistance levels to BCN and external/internal attributes have greatly improved in the past years, and variety testing is needed to provide updated characteristics for all varieties available on the Swedish market. The development of suitable resistant varieties is awaited to better deal with BCN pressure. At the same time, particular attention to BCN resistance development should be taken to ensure resistance properties are not bypassed by BCN populations.

Research results were communicated and published exclusively through non peer-reviewed, national (or bi-national⁸²), channels. Publications in peer-reviewed, international channels could increase the international visibility and inputs from peers. Most projects were, however, carried out by NBR, a member of the International Beet Research Institute (IIRB). The IIRB has a large international network, with members all over the world organized in study groups (e.g., pest and disease group). Study groups meet annually or bi annually to

⁸² NBR is present both in Denmark and Sweden so that trials are generally planned and communicated in both countries.

discuss joint research and trials. The latest results from research projects carried out by NBR are presented every other year at an international congress with several hundred participants (Olsson, personal communication). Besides this, the link between researchers, advisory services, and farmers seems well established, most likely due to the characteristics of the crop (small area, organization around sugar production). Particularly, the national farmer meetings held every spring and summer attract around 50 % of the Swedish beet growers (~600 persons, Olsson, personal communication). Nonetheless, no participatory approach was used in any of the research projects.

Through this work, additional needs for future R&D could be highlighted (Box 18).

Box 18: Integrated Management of Beet cyst nematode: Knowledge gaps identified in this report

Prevention/Monitoring

- Systemic approaches that account for multi pest and/or multi crops are lacking in BCN management and the planning of crop rotation. For instance, resistant trap crops for BCN such as oilseed radish and white mustard are hosts for *Plasmodiophora brassicae* which causes clubroot in oilseed rape. The risk of damage in oilseed rape should therefore be considered if both oilseed rape and resistant trap crops are used in the rotation.
- Validation of the DSS outputs with field data would be needed to confirm predictions, in case of the need for such DSS is proven.
- A mechanistic understanding of soil biota (which may be confounded with fertilization type) interactions with BCN development and its potential antagonist role might improve future preventive measures for BCN management.
- Improvements in terms of cost efficiency of variety testing could facilitate and reduce costs of variety trials.

In addition, careful assessment of the relevance of research projects in the sector might require more thorough attention in the future.

4. Weed management in arable crops

Weed management in annual crops grown conventionally mainly relies on chemical control whereas weed management in organic farming relies on mechanical control. Tillage is generally cost and labour intensive compared to chemical control (Ringselle 2015). Herbicides are the dominant PPP used in Sweden⁸³, where they account for more than 80 % of the total amount of PPPs sold for agricultural use. Herbicides are generally used after harvest and between crops. The steadily increasing amount of restrictions towards herbicide use and the low rates of new registration of active substances in the EU are raising concerns about conventional weed management in the future. The increasing development of herbicide resistance is certainly also of great concern in this context.

The case of Glyphosate (N-(phosphonomethyl)glycine) is of particular concern. The substance has been under evaluation for a possible renewal of the authorization in the EU since 2012⁸⁴. Its authorization for the EU was to be renewed in 2016 and has received an extension until 2018⁸³. After this date, it is unknown whether it would be kept or removed

⁸³ Chemical pesticides in agriculture - Facts about the use in Sweden 1981–2015 [original title: Kemiska bekämpningsmedel i jordbruket – Fakta om användningen i Sverige 1981–2015] (SSNC 2016)

⁸⁴ Frequently Asked Questions on Glyphosate. In European Commission – Fact-Sheet. Press Release Database. European Commission (2016)

from the market. It is the most common active PPP substance used in Sweden. It is primarily used to control annual broadleaf weeds and grasses on farmland in the spring before crop emergence and in the fall after harvest. It represents 35 to 45 % of all herbicide sold in Sweden in the past years (reaching 600–700 tons sold/year⁸⁵, mainly for agriculture⁸⁶).

An integrated approach to weed management is recommended by Jordbruksverket to farmers⁸⁷ with:

- The use of preventive measures, such as drainage, fertilization, crop rotation, seed density, tillage, delayed sowing time, and hygiene (both with the use of clean seeds and machinery);
- Field monitoring of weeds, which can be facilitated with the use of the weed database⁸⁶ and the book *Weed control on arable land* (Lundkvist 2014);
- An adapted control, with need-based actions, including the combination of control methods (i.e., chemical and mechanical);
- A follow-up of the results of actions.

A database⁸⁸ published by Jordbruksverket provides information on available chemical control, preventive measures and alternative control methods (mechanical control) against weeds in Sweden. Several notes are published annually by Jordbruksverket for advice on weed management in specific systems. Specific recommendations for weed management in organic cultivation are additionally published by Jordbruksverket (e.g., control of couch grass⁸⁹).

4.1. Research projects funded by Stiftelsen Lantbruksforskning and Jordbruksverket

A total of 11 projects have been granted during the period 2009–2014 that targeted integrated weed management with a total budget of 13.19 MSEK (Table 9). Research projects specifically dealing with weed management in potato and sugar beet production are not included due to their specific production characteristics.

Table 9: Research projects dealing with integrated management of weeds in annual crops (except in potatoes and sugar beets) funded by Stiftelsen Lantbruksforskning and Jordbruksverket in the period 2009–2014.

	#	Title (Institution)	Research category	Budget MSEK	(Call) Final
Prevention	F1a	Estimation of weed emerging status as a method to predict herbicide effect - basis for key decisions in IPM (SLU)	Biology	0.64	(2009) 2014
	F1b	Estimation of weed plant emerging status as a method to predict herbicide effect - basis for key decisions in IPM. Extension of Step 1: 2011 season (SLU)	Biology	0.22	(2011) 2014
	F2	Effective control of couch grass with reduced nutrient leaching - an adaptation to IPM (SLU)	Preventive measures	3.30	(2010) 2014
	F3	Control of black grass (<i>Alopecurus myosuroides</i> Huds.) through a variety of integrated farming scheme (SLU)	Preventive measures	1.34	(2012) 2014

⁸⁵ Sold quantities of chemicals [original title: Försålda kvantiteter av bekämpningsmedel] (Keml 2016)

⁸⁶ 648 tons out of 657 tons sold in Sweden in 2016 were used in agriculture. Data: *personal communication*, Keml.

⁸⁷ Chemical weed control 2017 [original title: Kemisk ogräsbekämpning 2017] Jordbruksverket report No. BE20 (Hallqvist, H., Johansson, L. and Widén, P., 2017)

⁸⁸

<http://www.jordbruksverket.se/etjanster/etjanster/odling/ograsdatabas.4.35974d0d12179bec28580002385.html>

⁸⁹ Measures against couch grass in organic production [original title: Åtgärder mot kvickrot i ekologisk produktion] (Jordbruksverket, 2016)

Optimization	F4a	Integrated weed control by row hoeing and row spraying in spring oilseed crops (SLU)	Alternative	0.72	(2011) 2014
	F4b	Integrated control of annual weeds by row hoeing and row spraying in annual crops (SLU)	Alternative	1.73	(2011) 2015
	F5	Mechanical control of thistle and sow-thistle - when to implement tillage (SLU)	Alternative	0.18	(2013) 2013
	F6	Mechanical and integrated control of black grass (<i>Alopecurus myosuroides</i> Huds.) (SLU)	Alternative	1.75	(2010) 2013
	F7	Climate robust cultivation with row hoeing against roots and seedlings of weeds in cereal (HS)	Alternative	1.20	(2011) 2016
	N6	Preliminary study of the possibility of adapting the Danish decision support system for weeds to Swedish conditions (JTI)	DSS	0.30	(2010) 2011
	F8	Inventory of herbicide resistance in Swedish weeds (SLU)	Resistance	0.95	(2012) 2013
	Knowledge summary	G2	Knowledge Summary - Integrated pest management (IPM) (SLU)		0.69
G5		Available technologies for row cleaning (HS)		0.17	(2011) 2014

4.2. Advances in Swedish research

4.2.1. Prevention

Diagnosis/Biology/Mapping

Andersson et al. (project **F1a&b**, final reports) aimed at developing methods to access the active growth stage of weeds to optimize weed control by better adapting timing of herbicide use. The project was only partially funded, so that only the first part could be carried out. They investigated weed reactions to water and temperature stress, and measured weed growth status. Different techniques were investigated. The plant photosynthetic capacity, calculated using the measure of chlorophyll fluorescence, was selected to measure weed growth status (Persson 2014). A large variation in the results was found so that no conclusion could be drawn. Preliminary results, however, encourage further investigation to ultimately develop methods for measuring plant stress in the field and optimizing weed control. No follow-up project has been funded so far.

Lundkvist and Verwijst (project **F5**, final report; Tavazira manuscript; Verwijst et al. in review) investigated the threshold (compensation point) for the mechanical control of cursed thistle (*Cirsium arvense*) and perennial sow-thistle (*Sonchus arvensis*). They found that the compensation point occurs before the five (cursed thistle) and six-leaf (sow thistle) stage then considered as compensation points. Mechanical control should be done before these stages, i.e., at an earlier time than the current recommendation for mechanical control. Sow- and cursed thistle should be controlled well before the five- and the six-leaf stage, respectively.

Preventive measures

Aronsson et al. (project **F2**, final report) investigated the effect of cover crop in controlling couch grass (*E. repens*). They show that that the cultivation of high yielding cover crops that are not composed of only leguminous plants (Yesudasan 2013; Ringselle et al. 2015, 2016b) can contribute to the resource efficient control of couch grass.

Nilsson et al. (project **F3**, final report) investigated the effect of sowing dates, varieties, and seeding rates to improve crop competitive ability and subsequent control of black grass (*A. myosuroides*) management in winter wheat. They show that:

- (1) Black grass density could be decreased by postponing sowing two to three weeks due to a better synchronization with seed dormancy.
- (2) The competitive properties of cultivars (e.g., varieties *Ellvis* and *Julius*), can lead to a significant reduction of black grass density, even without additional herbicide treatments.

They showed that crop competition abilities with weeds and increased knowledge of seed dormancy are effective tools for integrated strategies against black grass in winter wheat. Adaptation of crop management can improve the sustainable control of black grass and reduce the need and dependence on chemical control.

4.2.2. Monitoring

Method development

Ringselle (project **F2**, final report, 2015) developed a method to estimate couch grass (*E. repens*) density: the "grading fork". This method has been implemented to measure abundance in a "quick and easy way", so that comparison between treatments can quickly be assessed. The method, however, does not allow a measure of weed population size.

Åkerblom Espeby and Nilsson (project **F8**, final report) suggested a method to be used for routine screening of herbicide resistance. Petri-dish tests are generally recommended and are particularly well-adapted for wild poppies (*Papaver* spp.) and cornflowers (*Centaurea cyanus*). 'Cylinder tests' are, on the other hand, well-adapted for resistance testing of black grass (*Alopecurus myosuroides*).

4.2.3. Optimization of control

Decision support system

Olsson and Fogelberg (project **N6**, final report) investigated the possibility of adapting a Danish DSS for weed management, Planteværn Online (PVO)⁹⁰, to Swedish conditions. The programme had already been adapted to some countries in Europe and other countries are showing interest. A particular focus on dose reduction is taken in the Norwegian version of the DSS (VIPS). Through interviews with advisors and stakeholders in Sweden, a strong interest for such online support was revealed. The crops for which its development would be most beneficial were further identified. Winter- and spring oilseed rape, corn, winter wheat, spring barley, sugar beet, and fodder were identified in order of priority, followed by spring wheat and oats. They estimated the cost and time plan for an adaptation of the Danish database to Swedish conditions to a total of 10 MSEK over three years. After this development period, the annual functioning costs are estimated to a total of 1.2 MSEK, to which 5.5 MSEK are to be added to cover new field trials in case of new herbicide market authorization (per unit).

Alternative control methods - Mechanical control (alone or in combination with chemical control)

Aronsson et al. (project **F2**, final report) investigated resource efficient strategies to control couch grass (*E. repens*) without use of herbicide or intensive tillage, together with prevention of nutrient leaching. They show that optimized single-tillage one to five days after harvest (Ringselle et al. 2016a) can contribute to the resource efficient control of couch grass. If no cover crop is grown, mowing and row hoeing can reduce couch grass biomass. In addition, a reduction of nitrogen leaching was achieved by the combined use of cover crop and both row hoeing and mowing (Aronsson et al. 2015). The study also indicated that phosphorus leaching might require specific attention. In systems with low pressure from couch grass, the use of cover crop together with row hoeing or mowing, instead of more intensive tillage is therefore recommended. It is concluded that a site-specific approach is needed to best optimize weed control.

Lundkvist (project **G2**, 2014) and Håkansson (project **G5**, final report) compiled existing knowledge on available methodology for integrated weed management and mechanical control.

Andersson et al. (project **F6**, final report) studied the effect of mechanical control against black grass (*A. myosuroides*) and broadleaf weeds alone or in combination with chemical control. Best control was achieved with a combination of mechanical (false seed bed before

⁹⁰ Crop protection online, available for registered users www.ipmdss.dk

sowing and harrowing) and chemical treatments. The combination of treatments showed a synergistic effect whereas a selective weed harrowing alone did not provide sufficient control. Such combination reduced weed pressure between 30-70 % the next summer (black grass: -30 to -50 %; broadleaf: -40 to -70 %), with one chemical treatment, instead of two generally applied. A selective weed harrowing in autumn combined with chemical control in the spring is therefore recommended and can reduce the use of herbicide and enhance its effect. This, in turn, would result in a decreased risk of herbicide resistance development. The use of mechanical control is, however, weather permitting and its applicability also varies according to soil types, with better effect on easily processed loose soil, and weaker effect on soils with a high clay content particularly in the case of high black grass pressure.

Lundqvist et al. (project **F4**, final report) investigated the combined use of intra-row spraying and inter-row hoeing as mean to reduce herbicide use in spring oilseed rape, winter wheat, and field beans. They show that such a combination enabled a reduction of herbicide use, the extent to which increased with an increase of the distance between rows. In a pilot study, yield increase in treated versus untreated control was observed only in oilseed rape sites with high weed pressure (Nilsson et al. 2014), highlighting a site-specific approach for weed control. Further technology developments are needed to (1) improve line tracking using GPS and camera, (2) improve row spraying with sprayer nozzles with small holes. Weed control based on combined row spraying and row hoeing is, however, weather dependant as row hoeing cannot be implemented in case of high soil moisture.

Ståhl et al. (project **F7**, final report) studied weed control by row hoeing at 50 cm row spacing, with a focus on winter and spring wheat. They found improved control compared to 25 cm row spacing in winter wheat whereas no difference was found in spring wheat. In addition, they studied the effects of row spacing and seeding rates on crop yield and found considerable yield variation in cereals sown using 25 cm- or 50 cm row spacing using same seeding rate. Only a small yield reduction was observed, which varied according to line width: 5–7 % reduction at ~12 cm line width and 10–12 % reduction at ~2 cm width sown in double line. Ståhl et al. (*Id.*) then investigated the optimal number of interventions needed for best weed control. They showed that two row hoeing interventions at 50 cm row spacing generally provided the same control and led to unchanged yield when compared with a third intervention after ear emergence. However, this effect seemed to vary in relation to nitrogen supply and species-specific weed pressure. This could be explained by the fact that (1) interventions are adapted to cursed thistle (*C. arvensis*) development and were done too late for an optimal couch grass (*E. repens*) control (see also project **F5**); and that (2) some weeds such as couch grass benefit from highly-available nitrogen. Control of perennial sow-thistle (*S. arvensis*) was well achieved by row hoeing while the effect on cursed thistle were variable according to their initial density, with an increased pressure observed when hoeing occurred at low initial density.

4.2.4. Efficacy of PPPs: Herbicide resistance

Åkerblom Espeby and Nilsson (project **F8**, final report) investigated the status of herbicide resistance in Swedish weeds. The aim of this project was to study the status of weed resistance to ALS-inhibiting herbicides (particularly sulfonylurea) and develop a method for future herbicide resistance screening. The results indicate that resistance to sulfonylurea herbicides was common for chickweeds (*Stellaria media*) and blackgrass (*A. myosuroides*) sampled in Swedish fields, and could be found for the common poppy (*Papaver rhoeas*) sampled in Östergötland. Resistance to cycloxdim was also found for some samples of black grass. No resistance to herbicide was found for cornflower (*Centaurea cyanus*) (Gustafsson 2014). Further experiments aim at investigating the resistance status of melde (*Chenopodium album*), hemp-nettle (*Galeopsis* spp.) and smartweed (*Polygonum* spp.).

4.3. Additional field trials

Trials focusing on weed management of annual crops are included in the national field trials supported by Stiftelsen Lantbruksforskning annually. Herbicide trials (including herbicide blend) in cereals, oilseed rape, and maize are carried out yearly, with a focus on weed density after herbicide treatments in autumn and in spring, crop yield, and costs. Different weed varieties/types (broad leaves, grasses) are targeted by different trials. Weed pressure is further tested under different termination treatments (ploughing, reduced tillage) at different herbicide treatments for winter oilseed rape. Field trials with a focus on weed (black-grass) pressure according to spring wheat variety and sowing time were also set up in 2016.

4.4. Communication

The results of the projects have been communicated mainly in popular channels. The results from one project (F2) were communicated through peer-reviewed publication (included in one PhD thesis and two MSc theses). Means of communication are summarized in Table 10.

Table 10: Publications and communication of results [1: presence, in addition to final reports] from projects with focus on weed management funded by Stiftelsen Lantbruksforskning in the period 2009–2016. In green: published and searchable publication (+ manuscript). In orange: publication/communication channels not found online. In red: no publication/communication found.

	Popular publication		Peer-reviewed	Scientific publication		Conference		Education	
	Online	Print		Conference proceeding	Manuscript	National/regional	International	PhD	MSc/ BSc (manuscript)
F1									1
F2	1		1			1	1	1	1 (+1)
F3		1				1	1		
F4	1	1							
F5	1				1	1		(+1)	
F6	1	1				1			
F7		1				1	1		
F8	1	1				1	1		1
G2	1	1				1			
G5									
N6									

Peer-reviewed publication

- Aronsson, H., Ringselle, B., Andersson, L. & Bergkvist, G. (2015) Combining mechanical control of couch grass (*Elymus repens* L.) with reduced tillage in early autumn and cover crops to decrease nitrogen and phosphorus leaching. *Nutrient Cycling in Agroecosystems* 102:383–396. [Project F2]
- Ringselle, B., Bergkvist, G., Aronsson, H. & Andersson, L. (2015) Under-sown cover crops and post-harvest mowing as measures to control *Elymus repens*. *Weed Research* 55:309–319. [Project F2]
- Ringselle, B., Bergkvist, G., Aronsson, H. & Andersson, L. (2016a) Importance of timing and repetition of stubble cultivation for post-harvest control of *Elymus repens*. *Weed Research* 56:41–49. [Project F2]
- Ringselle, B., Prieto-Ruiz, I., Andersson, L., Aronsson, H. & Bergkvist, G. (2016b) *Elymus repens* biomass allocation and acquisition as affected by light and nutrient supply and companion crop competition. *Annals of Botany* 119:477-485. [Project F2]
- Verwijst, T., Tavaziva, J. & Lundkvist, A. (in review) Effects of competition, root weight and burial depth on the compensation point of *Cirsium arvense*. [Project F5]

PhD thesis

- Ringselle, B. (2015) Resource efficient control of *Elymus repens*. PhD thesis, SLU (Uppsala, Sweden). [Project F2]

Tavaziva, J. (manuscript, expected 2017) Effects of integrated pest management (IPM) on the population dynamics of the perennial weed species *Cirsium arvense* (L.) Scop. PhD thesis, SLU (Uppsala, Sweden). [Project F5]

MSc/BSc thesis

Persson, M. (2014) Effekt av torkstress på tillväxt hos annuella ogräs. MSc thesis, SLU (Uppsala, Sweden). In Swedish [Project F1]

Prieto Ruiz, I. (manuscript, expected 2017) MSc thesis. [Project F2]

Yesudasan, J. (2013) Effects of rye-grass and red clover on morphology and biomass allocation in couch grass. MSc thesis, SLU (Uppsala, Sweden). [Project F2]

Gustafsson, I. (2014) Känsligheten hos blåklint mot en ALS-inhibitor. MSc thesis, SLU (Uppsala, Sweden). In Swedish [Project F8]

Final reports

Andersson, L., Åkerblom Espeby, L. and Weih, M. (2014). Uppskattning av ogräsplantans tillväxtstatus som metod att förutsäga herbicideffekten – underlag för beslutsnyckel i IPM. Final report for Stiftelsen Lantbruksforskning number H0960245 & V1160042. [Project F1]

Andersson, A., Hansson, D., Nilsson, A. TS., Svensson, S-E. (2013). Mekanisk och integrerad bekämpning av renkavle (*Alopecurus myosuroides* Huds.). Final report for Stiftelsen Lantbruksforskning number V1033030. [Project F6]

Aronsson, H., Ringselle, B., Andersson, L., and Bergkvist, G. (2014). Effektiv kontroll av kvickrot med minskat näringsläckage - en anpassning till Integrerat växtskydd. Final report for Stiftelsen Lantbruksforskning number H1033012. [Project F2]

Åkerblom Espeby, L., and Nilsson, A. TS. (2014). Inventering av herbicidresistens i svenska åkerogräs. Final report for Jordbruksverket number 10417. [Project F8]

Lundkvist, A. (2015) Kunskapssammanställning - Integrerat växtskydd (IPM). Final report for Jordbruksverket number 11834. [Project G2].

Lundkvist, A., and Verwijst, T. (2013). Mekanisk bekämpning av åkertistel och åkermolke: När ska man egentligen genomföra jordbearbetning? Final report for Jordbruksverket number 10502. [Project F5].

Lundkvist, A., Algerbo, P-A., Andersson, A., Gilbertsson, M., Hansson, D., Nilsson, A. TS., Ståhl, P., Stenberg, M., Verwijst, T. (2015) Integrerad ogräsbekämpning genom radhackning och radsprutning i våroljeväxter / Integrerad bekämpning av annuella ogräs genom radhackning och radsprutning i ettåriga grödor. Final report for Jordbruksverkets number 11832 & 11218. [Project F4a/b]

Nilsson, A. TS., Andersson, A., Hansson, D. (2014) Sätidpunkter, sorter och utsädesmängder i renkavleproblematiken. Final report for Jordbruksverket number 2928. [Project F3]

Olsson, J. and Fogelberg F. (2011). Förstudie över möjligheten till att anpassa den danska beslutsstödsystemet för ogräs till svenska förhållanden. Final report for Jordbruksverket number 12086. [Project N6]

Ståhl, P., Stoltz, E. and Wallenhammar, A-C. (2016). Klimatrobusta odlingssystem med radhackning mot rot- och fröogräs i stråsåd. Final report for Stiftelsen Lantbruksforskning number H1160130. [Project F7]

Håkansson, K. (2014) Tekniker för radrensning i och mellan raderna. Final report for Jordbruksverket number 11842. [Project G5]

4.5. Implementation

4.5.1. Current Farming practices⁹¹

Chemical and mechanical control

Little implementation of the results from research projects targeting integrated weed management is found in practice. To date, most farmers rely on herbicide treatment in the fall and/or spring, mainly with Glyphosate to manage weeds without using any DSS. Instead, chemical control is generally carried out on the basis of recommendations from sellers, user

⁹¹ Data presented here is based on an interview with an advisor expert in weed management in Sweden: A. Adholm (HS).

manuals, advisors using knowledge on compensation points, and the farmers' own experience.

The combination of chemical with mechanical control is rare in cereal production. In contrast, such combined control is common for sugar beet growers, and, to a lesser extent, maize growers. The management option is chosen according to its cost, with farmers choosing the cheapest option available. Machinery for mechanical weed control (e.g., 'Cameleon') represents a large investment for conventional farmers who generally have all the machinery for chemical control. Mechanical weed control is, in addition, weather-dependent so that it is both easier and cheaper for farmers to control weeds chemically. However, mechanical control can sometimes be the only option to manage certain weeds. In this case, timing for mechanical control is based on the farmers' own experience as well as information from advisors in special cases (e.g., black grass).

Prevention of herbicide resistance

Farmers use measures to prevent the development of resistance by alternating active substances (when available), adjusting the doses, and spraying on young weeds. If resistance is observed, farmers select another substance if available, increase doses, combine with mechanical control and preventive measures (crop rotation, variety, and soil cultivation methods), and take measures to limit the spread of seed as far as possible. Concerns about a further development of herbicide resistance are found among advisors.

Black grass has been a large and increasing problem in recent years and farmers are aware of its resistance to herbicides. In fields suffering high black grass pressure, preventive measures such as false seed-bed, delayed sowing, increased seeding density, use of competitive varieties, and cleaning of machinery to prevent its spread are used in combination with chemical control.

4.5.2. Field trials and advisory services

Herbicide resistance monitoring

Samples of predominant weeds are taken annually by Jordbruksverket and analysed for resistance in collaboration with Aarhus University (Denmark). Results are published in Jordbruksverket letters about weeds⁹² to farmers and the general risk of resistance to different herbicide groups are summarized in a national publication⁹³. Farmers have the possibility to send weed samples to Jordbruksverket when resistance is suspected (H. Hallqvist, personal communication).

Field trials

No implementation of the research results presented here within the national field trials could be found.

Decision support system

The implementation and maintenance costs for a DSS for weed control have been considered to be too expensive for Jordbruksverket. Instead, a weed database has been made available online. Information on chemical management (chemicals available, dose and cost per ha) is available for all weed species, while little information is available on mechanical methods and preventive measures. The database is generally used by advisors in need of information on chemicals to control a specific weed species. Costs indicated seem to not always be accurate.

4.6. Discussion

Most of the 11 IPM projects targeting weed management in annual crops, funded by Stiftelsen Lantbruksforskning and Jordbruksverket during the period 2009–2016 with a total

⁹² Original title: Jordbruksverkets ogräsbrev

⁹³ Resistance, Herbicide Resistance, Fungicide Resistance, Insecticide Resistance [original title: Resistens, Herbicidresistens, Fungicidresistens, Insekticidresistens] publication number OVR292 (Jordbruksverket 2016)

budget of 13.19 MSEK, dealt with alternative control measures (mainly mechanical control), as well as with preventive measures, and knowledge about weed biology for improved control. One project investigated the status of herbicide resistance, and another analysed the possibility to adapt the Danish DSS for weed management in Sweden.

The interview with one field advisor revealed that the implementation of research results was rare, and that weeds are a large concern for farmers. The status and development of black grass resistance to herbicides is particularly alarming and, when encountered, alternative measures can be undertaken. Implementation of mechanical control in combination with chemical control is rarely found in practice, and is mostly limited to sugar beet growers. No DSS is currently available for weed management, and such a tool could find interest among advisors and growers. For instance, a collaboration to develop a Swedish version of existing DSS such as IPM-wise available to help Danish farmers with weed management could be encouraged. In addition, the monitoring of herbicide resistance is currently done in collaboration with Aarhus University (Denmark) so that there has been no implementation in practice of the results of the pilot study aiming at developing methods for such monitoring.

4.7. Conclusion

The current weed management strategy, which mostly relies on chemical control, seems to be facing difficulties for the coming years due to the development of herbicide resistance and the possible removal of active substances from the market. Advances in Swedish research in the period 2009–2014 have pointed out the potential for optimized control using row-spraying and mechanical weed control that can be combined with chemical control. The method is still in development and, so far, no implementation of this procedure is observed, even though these results had been communicated to farmers and advisors through local channels. Furthermore, no overall reduction of herbicide use (based on data of sold substances⁹⁴) and reliance on chemical control is observed.

The recent completion of research projects might explain such a pattern, but also the fact that collaboration between different stakeholders (academia, industry, advisory services) was missing from most research projects. In addition, external factors such as maturity of the technology, costs and availability of material, but also the contrasted apparent simplicity of chemical control compared to these alternative methods might be slowing down implementation of research results. Policy incentives to promote the use of these technologies, and the use of a participatory approach in future research projects might improve implementation of research results in practice. In addition, a completely integrated approach to pest management, including several measures for weed control is essentially absent from the national field trials. Instead, these trials are currently addressing the cost and efficacy of different active substances to control weeds and their impacts on yield. In contrast, none are testing the potential alternative control methods or other IPM aspects.

Through this work, additional needs for future R&D could be highlighted (Box 19).

⁹⁴ Sold quantities of chemicals [original title: Försålda kvantiteter av bekämpningsmedel] (KemI 2016)

Box 19: Integrated Weed Management: Knowledge gaps identified in this report

Optimization of control

- There is a need for R&D of economically viable integrated strategies to reduce reliance on herbicides for weed management, as well as to prevent and manage herbicide resistance in Sweden (Neve 2007). Particular attention should be given to the impact of reduced doses of herbicide in resistance development (see e.g., Neve and Powles 2005), particularly within the national field trials.
- Data on the efficacy and costs, in the short- and long terms, under natural conditions would be needed to promote the use of optimized methods or alternative methods (row-spraying, mechanical control). Upscaling of these trials to demonstration farms and/or annual and/or long-term field trials could provide such data.
- Studies of the effect of reduction of herbicide use (dose, frequency) on yield are lacking in Sweden. Recent research has shown, using a network of privately managed farms, that low pesticide use rarely decreases farm productivity and profitability (Lechenet et al. 2017) and that no correlation between herbicide application rates and weed abundance or yield was found, with the exception of less abundant weed species not targeted by farmers (Gaba et al. 2016).
- The development of a DSS to help farmers adopt integrated weed management strategies and prevent weed resistance development in Sweden, for instance through collaboration with developers that already provide such a service (e.g., IPM-wise in Denmark).

Other

- A holistic approach, taking into consideration weed management over a multi-year period is lacking.
- Collaborative (involving different actors such as advisory services, industry and/or researchers) and/or participatory research (involving farmers), could improve implementation of research results (particularly mechanical control) in the future.

5. Research implementation: discussion based on the specific research areas

Implementation success as a result of a funded project is difficult to assess. Results can enter at different stages of the knowledge chain, from implementation in different stage of research, to usage in industries, field trials or adoption by farmers. The analysis of the four case studies shows that the level of implementation of research findings and IPM adoption varied between crops and research projects. Many projects have provided a foundation for new studies while only a few have led to product development or guidance ready for implementation.

Result implementation and adoption by advisory services and farmers was generally good for BCN management using tolerant varieties in sugar beets but weak for integrated weed management in annual crops. Results and recommendations were, however, taken and communicated to farmers by national advisory services. Research findings on advanced method development in breeding programmes were done in close collaboration with industry and directly integrated into their breeding programmes, although additional research is needed before the commercialization of new resistant varieties. This research has generated a competitive edge for the involved industrial partner. The commercialization of new varieties will, however, require many more years of research so that a short-term implementation from research to farmer is not realistic. Research findings in relation to

national field trials were generally implemented with different levels of success. Many projects have resulted in further research (often still ongoing), so many results need additional research before they provide fully developed new products (or strategies) ready for implementation. Particularly, no DSS have been fully developed or adopted so far but their potential to reduce pesticide use is promising.

In other cases, non-scientific causes have probably slowed down market introduction or approval. For example, the cost of implementation of alternative methods such as investment in new machines for mechanical weed control might discourage farmers and advisory services. The development of political incentives such as insurance schemes to help farmers adopt alternative control management practices could promote their adoption, and see their costs reduced in the long run. Cost of development and maintenance of DSS has been highlighted as a barrier to its adoption. Similarly, most studies only focused on a single aspect of production, such as seasonal yields or variety resistance properties, rather than long-term socio-economic values. Some suggested measures might therefore not be the most economically viable for farmers and society in current farming climate but might still be useful knowledge for a future agriculture.

In addition, research projects generally focused on a single aspect of IPM, and there was no strategic coordination among the projects to integrate different aspects of IPM to promote its implementation. A strategic agenda and coordinated programme including testing under field conditions could improve this aspect in the future. Similarly, to enhance adoption and applied relevance of research, the development of interfaces where farmers and other key stakeholders could communicate needs and resources to researchers before and while designing research projects and be given opportunities to participate in the projects and provide feedback might improve the adoption of project findings (described in the theoretical framework for IPM implementation, Dent 2000, Appendix 7). Pilot farms could play a role for such implementation under field conditions. As an example, a network of over 2,900 farms spread over the country is being developed in France (DEPHY network, with the aim to reach 30,000 in the future), with the goal to adopt and disseminate good practices and provide feedback to researchers from the farm level (Guichard et al. 2017). It is worth noting that there has been no project within major crops done directly in collaboration with farmers under actual field conditions.

Overall, there is currently no indication that the overall aim of the EU-directive, namely to decrease PPP dependency, has been achieved over the past years in major crops in Sweden. So far, no decrease in sold quantities of pesticides targeting major pests (fungal diseases in cereals and potato, weeds) was observed in Sweden over the past years⁹⁵. However, Swedish use of PPPs is, in terms of hectare dose of fungicides and insecticides, as much as 90 % lower than the EU-average whereas use in terms of hectare dose of herbicides is at levels similar to the EU average⁹⁶. Data on sold quantities do not, however, allow a direct translation to variation in the degree of PPP dependency due to the variation in concentrations and toxicity of active substances. So far, there are no indices published for the degree of dependance on chemicals in Sweden (see e.g., IFT: Indicator of treatment frequency, NODU: Number of unit dose, INRA, France).

Strengths, weaknesses, threats and opportunities concerning implementation of IPM research identified in this synthesis report are summarized in Box 20. Organizational deficiencies in national research coordination were also highlighted as a general threat for implementation of IPM research in Europe (Dachbrodt-Saaydeh 2015). In addition, results from the EU-project concluded that promoting links and joint initiatives to increase awareness of consumers for IPM could facilitate IPM research implementation (Dachbrodt-Saaydeh 2015).

⁹⁵ Sold quantities of chemicals [original title: Försålda kvantiteter av bekämpningsmedel] (KemI 2016)

⁹⁶ Eurostats, in: Chemical pesticides in agriculture - Facts about their use in Sweden 1981–2015 [original title: Kemiska bekämpningsmedel i jordbruket – Fakta om användningen i Sverige 1981–2015] (SSNC 2016)

Box 20: Strengths, weaknesses, threats and opportunities for implementation of research findings within IPM, based on four case studies

<p>Strength</p> <ul style="list-style-type: none"> • Evidence-based recommendations generally provided, sometimes peer-reviewed • Good link with the breeding industry, advisory services, and, in some case, national field trials • Good dissemination of research results to advisory services • Variable rate and levels of implementation. 	<p>Weaknesses</p> <ul style="list-style-type: none"> • Low rate of projects resulting in developed products/strategies • Variable rate and levels of implementation • Implementation not always based on evidence-based conclusions • No general adoption of DSS • Short-term implementation not always realistic (i.e., breeding programmes) • Low EU-/international visibility.
<p>Opportunities</p> <ul style="list-style-type: none"> • Standardize scientific quality and fund large projects that address multi-aspects of the knowledge chain, to promote the full development of product/strategies • Develop a strategic research agenda for implementation of IPM in major crops, such as for the adoption of DSS • Promote the registration of biological agents in collaboration with industry and governmental agencies • Promote participatory approaches and the use of demonstration farms and long-term field trials to further develop and implement IPM research results under field conditions • Develop incentives to promote the implementation of alternative methods • Monitor farmers' reliance on PPP and IPM adoption. 	<p>Threats</p> <ul style="list-style-type: none"> • Difficulty to test/register new PPPs (biological or chemical) in Sweden • Cost for implementation of alternative methods vs. direct cost of pesticides • Availability of cheaper control methods (chemical or alternative) in other countries • Focus on seasonal yield rather than long-term socio-economic value.

IV. Concluding remarks and future directions for research

Following the European directive 2009/128/EC on the sustainable use of pesticides, Sweden requires all farmers to use Integrated Pest Management (IPM) since January 1, 2014.

Funding initiatives for research were taken to improve its adoption in practice by the Swedish Board of Agriculture (Jordbruksverket) and the Swedish Farmers' Foundation for Agricultural Research (Stiftelsen Lantbruksforskning) with large financial support from the Swedish government. These initiatives have resulted in 110 studies, for a total budget over 100 MSEK funded by Stiftelsen Lantbruksforskning (85 % budget) and Jordbruksverket (15 %). The overall aim of these studies was to generate new knowledge in the field of IPM to ensure the adoption of the directive and of national environment policies without any loss of competitive edge. A large part of the total budget was allocated to four major study areas that are of main importance for the Swedish agricultural sector due to their impact on harvest yield, farm economics, environmental, and public health. These areas were:

- (1) *Fusarium* infection in cereals,
- (2) *Phytophthora* infection in potatoes
- (3) Beet cyst nematodes (BCN) in sugar beets
- (4) Weeds in arable crops

This report constitutes an overview of these calls and projects' outputs, as well as, for the four major study areas, implementation of results in practice in the period 2009–2016. The main outcomes of this synthesis report and subsequent recommendations are summarized below.

This report shows that considerable advances have been made in the field of IPM in Sweden, both in terms of research and implementation in practice in different cropping systems. Advances in unravelling the mechanisms of fungal infections and in the development of molecular approaches to increase plant resistance were achieved in the two first systems mentioned above. Furthermore, detection methods for soilborne pathogens in different cropping systems have been developed and have resulted in commercially available soil analyses to prevent yield loss. The outputs of all above-mentioned projects have undoubtedly further contributed to the development of advanced molecular methods that are not restricted to the studied systems. These projects were generally done in close collaboration with industry and results have been implemented in ongoing breeding programs or resulted in service commercialization. The supported research has therefore generated a substantial competitive edge not only for the involved industrial partner or academic institution but also to the Swedish farmers. The commercialization of new resistant varieties will, however, continue to require more years of development. In view of the heavy use of fungicides in potato crops and of the need for new varieties adapted to Swedish conditions, the support to the potato breeding programme is highly warranted. Additional advances have been achieved in other cropping systems. Particularly, a kairomone to monitor fruit moths in apple orchards has been developed and patented with the aim to decrease insecticide use in this generally insecticide intensive system.

In addition, several more practice-oriented projects were also supported through the calls. Specific responses about the status of pest resistance to insecticides and herbicides were provided. Some projects have contributed to the implementation of new field trials now run on an annual basis and to advanced knowledge of preventive measures. Particularly, projects within the field of integrated weed management and of integrated management of potato late blight have provided practical support for a reduction of pesticide use. The dissemination of research results with potential for direct implementation was generally successful to Jordbruksverket, and led to the integration of results-based recommendations in notices published for farmers. However, the adoption of this guidance by farmers has, to date, generally been slow. This is probably partly due to the availability of chemical control and to insufficient economic incentives for implementation, as well as, in some case, the

short time after project completion. However, consumers' demand for foodstuffs produced with reduced chemical inputs increases so that the data generated through these research projects will likely contribute to changes in agricultural practices in the future. Whether these research projects have provided answers to the future challenges of agricultural production is currently difficult to foresee.

Nevertheless, IPM adoption still faces many challenges, which call for continued efforts in R&D with an IPM focus. Particularly, some knowledge gaps defined as specific targets of research calls have remained unanswered. These targets were either not targeted by any of the funded projects, or no ready-solutions have been determined by the funded projects. Furthermore, some projects were implemented although results were not well-evidence based, in which case some problems could eventually be faced.

Based on the outcomes of this synthesis, suggestions for future calls to support IPM adoption and the implementation of evidence-based research outputs are compiled and listed below.

- **Funding of large research projects should be facilitated and cooperation between funding bodies improved.** Each granted study had, in general, a relatively low budget, and one single research project was often funded through a diversity of applications granted from one or both funding bodies. Multi-actors were often involved who were, in some cases, individually funded through individual applications. Additional co-funders, such as private or public research foundations, were often mentioned. In addition, some applications received only a partial funding of the requested budget. The granted research projects were generally not coordinated and each focused on a single aspect of IPM. In contrast, multi-year projects involving multi-actors and a strategic coordination to integrate different aspects of IPM were rare. Nevertheless, some projects provided evidence-based answers to the initial question with a single funding application, whatever the size of the budget.
- **Overall quantity and quality of outputs should be improved.** The research projects with IPM focus included in this synthesis report varied greatly in their scientific quality and outputs. Overall, 37 % (+14 %, manuscript in preparation) of the granted projects accounting for 46 % (+15 %) of the budget invested has resulted in the publication of at least one peer-reviewed publication (international journals, academic work, patent). This despite the fact that there are lots of international scientific journals publishing applied research, results of field trials, and method development. Such publication, for small and large projects, assures knowledge transfer and continuity of the research and provides a quality assessment of the work as well as feedback from peers. In addition, only a marginal proportion of projects has been carried out with international collaboration, and a single project was part of a larger EU-project.
- **Accessibility and long-term availability of data and research results should be improved.** The final report was, for some projects, the only written scientific output and was, in a few cases, not accessible online. This calls into question the visibility and long-term accessibility of the research outcomes. In addition, the final reports varied greatly in terms of information presented and quality. Particularly, 30 % of the final reports did not present any results from statistical analyses. In the case where the final report is the only publication of the project, the validity of the results must therefore be considered questionable. In addition to the final report, several projects have disseminated their results through popular channels. For these to be proper and relevant they, however, need have a good evidence base. The assessment of dissemination activities was, in some cases, tedious as some final reports did not include a summary of the activities undertaken to disseminate the results.

- **Implementation of evidence-based research results could be improved.** Implementation is difficult to assess and can face multiple barriers such as the maturity of the technology, its costs, the studied scale, constraining policies, and the availability and common use of other measures. Many projects included in this synthesis have provided a basis for new studies while only a few have led to product development or guidance ready for implementation. The analysis of the four case studies has shown that evidence-based results from research projects were generally well taken in recommendations to farmers published by national advisory services. In addition, a few projects targeted very early phases of method development so that implementation within the timeframe defined in the research calls is quite unlikely. Some of these projects have further resulted in new successfully granted research projects sometimes still ongoing. On the whole, stakeholder collaborations were found to be essential for implementation.
- **Examples of excellent projects should be followed.** Going through the projects selected for this synthesis report, projects that perform well on all the assessed aspects of evidence quality, outputs dissemination, and implementation were found. These projects can be used as role models for future funding initiatives within IPM. Characteristics of these projects with a solution-focused question immediately relevant for Swedish agriculture include:
 - *In terms of project leadership:* (1) close collaborations between practitioners/advisors with access to a dissemination network and a person with a good research background and track record in terms of research and scientific dissemination and (2) good coordination and strategy among efforts to solve a specific problem.
 - *In terms of outputs:* (3) quality-assured open evidence (i.e., data available, statistical analyses, peer-review publications) and (4) wide dissemination of results using several channels some of which are available widely on the internet in the long term - e.g., in libraries, databases.

Recommendations for future calls

- **Quality of the research should be improved to enable implementation of evidence-based results.** Improvement of the quality of the study outputs should be encouraged. A stricter distribution of research funds based on scientific expertise and track record should be encouraged to improve scientific quality of the research projects and the implementation of evidence-based solutions. A two-step selection procedure has been adopted in 2014 by Stiftelsen Lantbruksforskning in that sense. Publications through peer-review channels should be encouraged.
- **Research projects need access to dissemination networks.** A broader dissemination should be encouraged to expand the audience of the projects' outputs nationally and internationally and promote the implementation of evidence-based results. Tight connections between researcher and different stakeholders including advisory services and farmers are encouraged to secure implementation in practice. In addition, online and long-term availability of popular publications of all studies, with at least a summary in English, should be promoted. Furthermore, a template for the final reports could be provided and their online accessibility secured in a database, including the reports of contracted studies by Jordbruksverket.
- **Opportunities for funding of large projects or coordinated collaborative efforts that integrate different aspects of IPM with a defined strategy to solve a relevant problem in the short- and long terms should be promoted.** Such a development would also decrease the number of applications needed to finance a research project and decrease the administration costs both from applicants and funding bodies. Improved collaboration between the two funding bodies, as well as with research councils, research foundations, and European efforts, is further encouraged to avoid overlaps between calls and support the funding of larger projects with a defined strategy.

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Appendices

Appendix 1. General principles of IPM as defined in the EU-directive 2009/128/EC (Annex III)

1. The prevention and/or suppression of harmful organisms should be achieved or supported among other options especially by:
 - crop rotation
 - use of adequate cultivation techniques (e.g., stale seedbed technique, sowing dates and densities, under-sowing, conservation tillage, pruning and direct sowing)
 - use, where appropriate, of resistant/tolerant cultivars and standard/certified seed and planting material
 - use of balanced fertilisation, liming and irrigation/drainage practices
 - preventing the spreading of harmful organisms by hygiene measures (e.g., by regular cleansing of machinery and equipment
 - protection and enhancement of important beneficial organisms, e.g., by adequate plant protection measures or the utilisation of ecological infrastructures inside and outside production sites.
2. Harmful organisms must be **monitored** by adequate methods and tools, where available. [...]
3. Based on the results of the monitoring the professional user has to decide whether and when to apply plant protection measures. Robust and scientifically sound **threshold values** are essential components for decision making. [...]
4. Sustainable biological, physical and other **non-chemical methods** must be preferred to chemical methods if they provide satisfactory pest control.
5. The pesticides applied shall be as specific as possible for the target and shall have the least side effects on human health, non-target organisms and the environment.
6. The professional user should keep the use of pesticides and other forms of intervention to levels that are necessary, e.g., by reduced doses, reduced application frequency or partial applications, considering that the level of risk in vegetation is acceptable and they do not increase the risk for development of resistance in populations of harmful organisms.
7. Where the **risk of resistance** against a plant protection measure is known and where the level of harmful organisms requires repeated application of pesticides to the crops, available anti-resistance strategies should be applied to maintain the effectiveness of the products. [...]
8. Based on the records on the use of pesticides and on the monitoring of harmful organisms the professional user should check the success of the applied plant protection measures.

Appendix 2. Characteristics of the publication channels for research results

Table 11 Different publication channels for research results and characteristics in terms of audience, access, data availability and peer-reviewing.

+++ / ++ / + / ± / -: Very good / good / correct / fair / poor

* includes industry, advisory services, and farmers

Type of publications	Audience		Long-term access	Data availability	Peer-review
	Scientists	Stakeholders*			
Peer-reviewed publications (open source/restricted access)	+++/++	±/-	+++	+ to +++ ⁹⁷	+++
PhD thesis (English/National language)	++/+	±	+++	+ to +++ ⁹⁸	++
Conference proceedings (online/restricted access)	+++/+	±/-	+++/-	-	+
MSc thesis (English/National language)	++/+	±	+++	+	+
Online report (National language) (indexed in database/not)	-/±	-/++	++/-	±	-
Fact-sheets (National language) (online)⁹⁸	-	+++	+++	±	± ⁹⁸
Trade press articles (National language) (online/printed)	-	+++	±/-	-	-

⁹⁷ Raw data can be uploaded as supplementary information with the article or to online databases and linked to the scientific publication/thesis. In case they are not, only available data (often analyzed) in the published article/thesis will remain available in the long run.

⁹⁸ Fact-sheets summarize data, results and conclusions published in a scientific publication (peer-reviewed or not) for stakeholders. They are archived in the website of the institution that carried the study and available online, and are often referred to in the recommendations published to stakeholders.

Appendix 3. List of studies targeting major crops

Table 12: Studies targeting major crops financed by Stiftelsen Lantbruksforskning and Jordbruksverket (mentioned after project reference number [*]) in the period 2009–2014 and completed to date. All studies with the same identifying number (#) constitute a single research project.

Call: year of application; Final: year of publication of the final report.

Studies strikethrough have not investigated the IPM focus described in the application.

	#	Reference	Title	Budget MSEK	Call	Final
Cereals (A)	A1	H1133073	Characterization of <i>Fusarium</i> resistant oat	2.20	2011	2013
	A2	H0936280	Development of genetic markers for resistance, quality and value for cultivation of oats	2.20	2009	2014
	A3a	6312 (*)	Pilot Project - Development of methods for testing the wheat and triticale varieties of <i>Fusarium</i> sensitivity and toxin production	0.50	2010	2010
	A3b	9811 (*)	Testing of wheat and triticale varieties of <i>Fusarium</i> sensitivity and toxin production	0.05	2011	2012
	A3c	V1260040	Continued testing of <i>Fusarium</i> susceptibility of wheat- and triticale varieties and pilot testing of <i>Fusarium</i> susceptibility of oats and barley varieties.	0.60	2012	2014
	A4	H1333237	Quick and reliable detection of <i>Fusarium langsethiae</i> with the "Loop-Mediated Isothermal Amplification" method	0.67	2013	2015
	A15	H1233053	Prediction of plant diseases based on molecular methods and spore traps (SLU)	2.13	2012	2016
	A5	H1060230	Comparison between visual grading and PCR technology to determine the attack of plant pathogens in wheat.	0.18	2010	2012
	A6	V1360014	Grading of field trials - more and easier or less with high precision	0.30	2013	2015
	A7	H1033263	Mapping of resistance to black spot disease of wheat and interactions with environment	2.95	2010	2015
	A9	H1033190	Development of plant diseases in future cropping systems with maize and winter wheat	1.25	2010	2015
	A8	H0933214	Towards IPM in wheat: Persistence of stem base pathogens on crop residues	1.98	2009	2015
	A10	H1133251	Prediction of deoxynivalenol (DON) in oats in western Swedish conditions using weather crop and management data.	2.10	2011	2015
	A11	10551 (*)	Seed transmittance importance of spreading the DON-producing organism <i>Fusarium graminearum</i>	0.13	2013	2013
A12	V1133036	Effect of genetic and phenotypic variation in <i>Puccinia striiformis</i> (wheat stripe yellow rust) on yellow rust epidemiology in Sweden	2.50	2011	2016	
A13	H0933039	Barley yellow dwarf virus in winter cereals - risk assessment and the effects of climate warming	1.20	2009	2014	
A14	11030 (*)	Which barley cultivar mixtures should we cultivate?	0.20	2014	2014	
Oilseed rape (B)	B1a	V1060004	Integrated control of grey field slug in oilseed rape	0.35	2010	2013
	B1b	V1160041	<i>Id.</i>	0.45	2011	2013
	B1c	11261 (*)	Integrated control and assessment of grey field slug in winter oilseed rape	0.35	2013	2014
	B1d	H1260038	Integrated control of grey field slug in oilseed rape. Risk assessment and adaptation of the control threshold	0.30	2012	2015
	B2	H0960029	Flea beetles in spring oilseed crops: How effective are current pesticides?	0.22	2009	2011

Table 12 (continued)

	#	Reference	Title	Budget	Call	Final
Potato (C)	C1	H1342236	Breeding of late blight resistant table potatoes for the whole of Sweden	2.00	2013	2016
	C2	11934 (*)	Leaf spots on potato leaves - it is always blight?	0.28	2011	2014
	C3	H0942155	Genetic diversity and aggressiveness of <i>Phytophthora infestans</i> in potato haulm and potato tubers	1.59	2009	2014
	C4a	H1042201	Biology and technology for improved land use in potato - driven cooperation for sustainable development of knowledge	7.67	2010	2016
	C4b	H1342225	<i>Id.</i>	0.75	2013	2016
	C5	H1142126	Field studies for sustainable control of potato late blight – cultivar resistance and induced resistance with phosphites can reduce the need for fungicides	2.55	2011	2016
	C6	10265 (*)	Economic considerations in the control of potato late blight and tuber blight	0.18	2013	2013
	C7	11962 (*)	Tolerance to strobilurin fungicides of <i>Alternaria solani</i> - the cause of blight in potatoes	0.35	2011	2014
	C8	H1142175	Blackleg - mapping of new pests in Sweden	0.70	2011	2014
	C9	5459 (*)	Ozone treatment of seed potatoes	0.11	2013	2013
	C10 a	H0942353	Increased profitability and sustainability in Swedish potato production systems through participatory research	0.01	2009	2010
	C10 b	H0942237	Optimized harvest - Optimized quality	0.05	2009	2011
	C11	4941 (*)	Optimized control of potato late blight	0.50	2010	2010
C12	6163 (*)	Forecast blight on the web / mobile	0.13	2011	2011	
C13	10671 (*)	Mechanical or chemical weed control in potatoes - advantages and disadvantages	0.07	2013	2013	
Sugar beets (D)	D1	H0944021	Survival of beet cyst nematode <i>Heterodera schachtii</i> in the biogas process	0.65	2009	2012
	D2	H1044234	Development of decision support for planning crop rotation in sugar beet production	0.85	2010	2013
	D3	H1144237	Influence of manure and ryegrass catch crop on beet cyst nematodes	1.40	2011	2016
	D4	V0944027	Testing of varieties of beet on nematode infested land	0.39	2009	2010
	D5	H1044070	The influence of different sugar beet varieties on population dynamics of the beet cyst nematode	0.34	2010	2012
	D6	11889 (*)	Validation and development of decision support tools for chemical control of leaf fungi in sugar beet	0.14	2012	2014
	D7	H0944128	Fighting strategies for leaf fungi in sugar beet - treatment in relation to different harvest times	0.40	2009	2011
	D8a	H0944124	Optimized weed control in sugar beets	0.29	2009	2011
	D8b	V0944024	<i>Id.</i>	0.28	2009	2010
	D8c	H1044053	<i>Id.</i>	0.25	2010	2012
	D9	H1144051	GPS guided weed control - the possibilities and limitations of sugar beet	1.56	2011	2015
	D10	V0944022	Programme for weed control in sugar beet	0.22	2009	2010
	E5	H1144056	The presence and influence of <i>Verticillium</i> and <i>Rhizomania</i> on sugar beets in Sweden	1.35	2011	2016
	E7	V0944023	Tolerance to soilborne fungi in sugar beet varieties	0.25	2009	2010
	E8	H1144057	Inventory of free-living nematodes in Swedish and Danish sugar beets.	0.10	2011	2014

Table 12 (continued)

	#	Reference	Title	Budget	Call	Final
Multi – soilborne diseases (E)	E1a	V0960049	Biological soil mapping in the field trial - DNA-based analysis of soil-borne plant diseases	0.90	2009	2015
	E1b	H0960195	Development of decision support for risk assessment of <i>Sclerotinia sclerotiorum</i> in spring rape by quantification of airborne infection, and studies of the infection process	0.74	2009	2014
	E1c	H0960323	Quick and reliable diagnosis of pathogens on red clover in soil and roots and thermal remediation of red clover seeds for increasing seed quality	0.60	2009	2013
	E1d	H1133275	Biological field mapping - Integrated analysis of soilborne plant diseases and soil chemistry in oilseeds and cereal - PHASE II	2.70	2011	2016
	E6	H0944111	The effect of oilseed rape and intercrops in a crop rotation with sugar beets	0.20	2009	2014
	E9	10553 (*)	Free-living nematodes in sugar beets and carrots - detection by PCR and class differences	0.21	2013	2013
	E10	H1142045	Correlations between potato stem canker and free-living nematodes	3.10	2011	2016
Multi - Weed management in arable crops (F)	F1a	H0960245	Estimation of weed emerging status as a method to predict herbicide effect - basis for key decisions in IPM <i>Id.</i>	0.64	2009	2014
	F1b	V1160042		0.22	2011	2014
	F2	H1033012	Effective control of couch grass with reduced nutrient leaching - an adaptation to IPM	3.30	2010	2014
	F3	2928 (*)	Control of black grass (<i>Alopecurus myosuroides</i> Huds.) through a variety of integrated farming scheme	1.34	2012	2015
	F4a	11832 (*)	Integrated weed control by row hoeing and row spraying in spring oilseed crops	0.72	2011	2015
	F4b	11218 (*)	Integrated control of annuals weeds by row hoeing and row spraying in annual crops	1.73	2011	2015
	F5	10502	Mechanical control of thistle and sow thistle - when to implement tillage	0.18	2013	2013
	F6	V1033030	Mechanical and integrated control of black grass (<i>Alopecurus myosuroides</i> Huds.)	1.75	2010	2013
F7	H1160130	Climate robust cultivation with row hoeing against roots and seedlings of weeds in cereal	1.20	2011	2016	
F8	10417 (*)	Inventory of herbicide resistance in Swedish weeds	0.95	2012	2014	
Knowledge summary (G)	G1	13598 (*)	Importance and opportunity of crop rotation for sustainable production	0.08	2010	2015
	G2	11834 (*)	Knowledge Summary - Integrated pest management (IPM)	0.40	2011	2014
	G3	10591 (*)	The role of plant rotation role in the control strategy for reducing the use of chemical pesticides	0.18	2013	2013
	G4	5462 (*)	Intercrops for reduction of soil pathogens	0.16	2013	2013
	G5	11842 (*)	Available technologies for row cleaning	0.17	2011	2014

Appendix 4. List of studies targeting other crops

Table 13: Studies targeting other crops financed by Stiftelsen Lantbruksforskning and Jordbruksverket (mentioned after project reference number [*]) in the period 2009–2014 and terminated to date. All studies with a same identifying number (#) constitute a single research project.

Call: year of application; Final: year of publication of the final report.

	#	Reference	Title	Budget MSEK	Call	Final
Forage crops (H)	H1	V1036016	Plant breeding of forage and barley for Northern Sweden	2.25	2010	2014
	H2	H1033099	Control of pests in clover seed with biological methods	1.50	2010	2014
	H3a	11659 (*)	Evaluation of bioassay for <i>Phytophthora pisi</i> on faba bean and pea. Test methods, choice of plants and field relevance	0.15	2011	2012
	H3b	H1133278	<i>Phytophthora pisi</i> and other root pathogens in faba bean. Inventory, interaction factors and growth strategies	1.50	2011	2015
	H4	H0960135	More protein and reduced weed pressure through intercropping of maize and faba bean in organic farming	0.95	2009	2013
	E1c	H0960323	Quick and reliable diagnosis of pathogens on red clover in soil and roots and thermal remediation of red clover seeds for increasing seed quality	0.60	2009	2013
Vegetables (I)	I1a	H1056021	Development of integrated control strategies against insect pests of cucumber in collaboration with growers	2.68	2010	2014
	I1b	H1256026	Development of integrated control strategies in greenhouse cucumber in collaboration with growers	1.92	2012	2016
	I2	10039 (*)	Application of biological pesticides in greenhouses	0.29	2013	2013
	I3	10971 (*)	Integrated pest management in vegetable growing in open field	0.60	2011	2013
	I4a	10587 (*)	Trials to limit <i>Acrothecium carotae</i> on carrots	0.20	2011	2012
	I4b	11886 (*)	Storage disease on carrots - the effect of growth period and variety	0.20	2011	2014
	I4c	11213 (*)	Biological control of <i>Acrothecium</i> -rot in carrots	1.44	2011	2014
	I5	H1156218	Catch Crops and physical separation of the growing fields that control strategies against the carrot psyllid	3.00	2011	2016
Orchards (J)	I6	V1356006	Insect screens and other measures to meet market requirements for product quality in the cultivation of turnip when the conditions for the control of cabbage root fly has changed.	0.46	2013	2014
	I7	10167 (*)	Production of plantation and sowing onion	0.06	2013	2013
	J1	V1036010	Map and control the European canker in apple	2.10	2010	2014
	J2	11826 (*)	What is that consuming apples during storage?	0.29	2011	2013
Berries (K)	J3	H0956324	Web-based forecast of tortricids - a pilot project of integrated control	1.40	2009	2012
	J4	H1156188	Development of integrated control strategies against insect pests of apple in collaboration with growers, advisors, pheromone producers and researchers	3.07	2011	2015
Willow (L)	K1	11848 (*)	Measures to control root diseases of strawberry	0.47	2014	2014
	K2a	H1056116	Integrated pest management of strawberry	1.00	2010	2014
	K2b	2313 (*)	<i>Id.</i>	0.30	2010	2010
	K2c	6371 (*)	Integrated pest management of strawberry (pilot project)	0.10	2011	2011
	K2d	11813 (*)	Integrated pest management of strawberry	0.42	2011	2014
	K3	11260 (*)	Dissemination methods for beneficial organisms in field cultivation	0.32	2013	2014
	L1	H1140095	Effects of mining method of willow cultivation in need of weed control as well as on returns in subsequent crops	0.64	2011	2014

Appendix 5. List of studies targeting non-crop specific aspects of IPM

Table 14: Studies targeting non-crop specific aspects of IPM financed by Stiftelsen Lantbruksforskning and Jordbruksverket (mentioned after project reference number) in the period 2009–2014 and terminated to date. All studies with a same identifying number (#) constitute a single research project. Call: year of application; Final: year of publication of the final report.

	#	Reference	Title	Budget MSEK	Call	Final
Biopesticides/Biostimulants (M)	M1	H0933088	Thiamine- a biocontrol agent in pest and disease management?	0.70	2009	2012
	M2b	H0956299	Bio-evaluation - Are biological control products that are available on foreign markets usable against plant diseases in Sweden?	1.20	2009	2016
	M2a	V1133033	Bio-evaluation - Are biological control products that are available on foreign markets usable as alternative control methods against plant diseases in Sweden?	2.30	2011	2016
	M3	9918 (*)	Coverage - oils	0.18	2009	2009
General aspects of IPM (N)	N1	10498 (*)	What is the cost of prevention in plant protection?	0.08	2013	2013
	N2	11865 (*)	IPM in Norway - a long-term work in a new era	0.05	2011	2014
	N3	11837 (*)	Digital pen and paper documentation in the field of integrated pest	0.60	2011	2014
	N4	V1160064	Integrated crop protection - experiences from 20 years of integrated crop production	0.21	2011	2016
	N5	H1133270	Pilot Farms can have an important role the introduction of integrated pest management on Swedish farms	0.18	2011	2013
	N6	12086	Preliminary study of the possibility of adapting the Danish decision support system for weeds to Swedish conditions	0.30	2010	2011

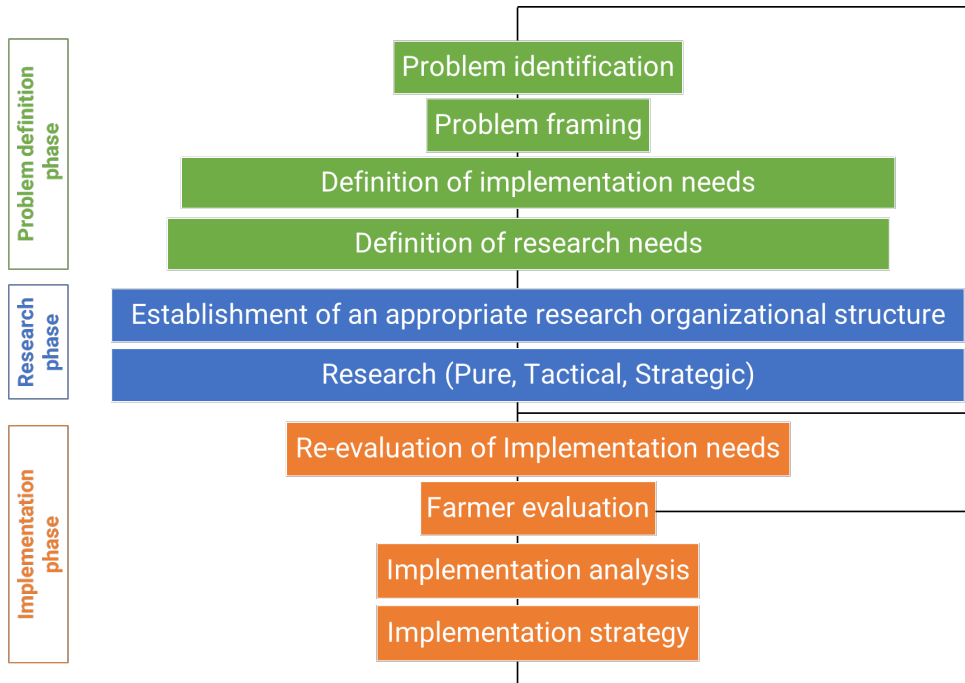
Appendix 6. Tolerated maximum levels for DON and ZEA in Europe

Table 15: Tolerated maximum levels for DON and ZEA (EU regulation CE N°1881/2006, and Jordbruksverket's recommendations⁹⁹) and T-2 and HT-2 (EU regulation CE N°2013/165) mycotoxins in cereals for livestock (grey shaded) and human consumption.

Toxin	Crop and use	Limit (µg/kg)	
DON	<i>Unprocessed cereals</i>	• Unprocessed cereals other than durum wheat, oats and maize	1,250
		• Unprocessed durum wheat, oats and maize	1,750
		• Cereals intended for direct human consumption, cereal flour (including maize flour, maize meal and maize grits), bran as end product marketed for direct human consumption and germ, pasta (dry) with the exception of foodstuffs listed below	750
	<i>Cereal grains/products for human consumption</i>	• Bread (including small bakery wares), pastries, biscuits, cereal snacks, and breakfast cereals	500
		• Processed cereal-based foods and baby foods for infants and young children	200
		• Unprocessed cereals, other than maize	100
ZEA	<i>Unprocessed cereals</i>	• Unprocessed maize	200
		• Cereals intended for direct human consumption, cereal flour, bran as end product marketed for direct human consumption and germ, with the exception of foodstuffs listed below	75
		• Maize, maize flour, maize meal, maize grits, maize germ and refined maize oil	200
	<i>Cereal products for human consumption</i>	• Bread (including small bakery wares), pastries, biscuits, cereal snacks, and breakfast cereals	50
		• Processed cereal-based foods (excluding processed maize-based foods) and baby foods for infants and young children (including maize-based food)	20
		• Barley (including malting barley) and maize	200
T-2 & HT-2	<i>Unprocessed cereals</i>	• Oats (with husk)	1,000
		• Wheat, rye and other cereals	100
		• Oats	200
		• Maize	100
	<i>Cereal grains for direct human consumption</i>	• Other cereals	50
		• Oat bran and flaked oats	200
<i>Cereal products for human consumption</i>	• Cereal bran except oat bran, oat milling products other than oat bran and flaked oats, and maize milling products	100	
	• Other cereal milling products	50	
	• Breakfast cereals including formed cereal flakes	75	
	• Bread (including small bakery wares), pastries, biscuits, cereal snacks, pasta	25	
	• Cereal-based foods for infants and young children	15	
	• Oat milling products (husks)	2,000	
	<i>Cereal products for feed and compound feed</i>	• Other cereal products	500
		• Compound feed, with the exception of feed for cats	25
		• Unprocessed cereals, other than maize	100

⁹⁹ Recommendations to minimize *Fusarium* toxins DON and ZEA in cereals [original title: Rekommendationer för att minimera fusariumtoxinerne DON och ZEA i spannmål] (Jordbruksverket, 2016)

Appendix 7. Theoretical framework for IPM research and implementation



References

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 Pilcher, C. L. 2001. Integrated pest management: an evaluation of adoption in field crop production. PhD thesis, Iowa State University (Ames, USA).