
Executive Summary:
The overall aim of PURE was to build a toolbox of approaches, methods and tools for implementing efficient IPM solutions in the challenging European context.

PURE provided IPM solutions in key European farming systems: annual arable farming systems (wheat-based and maize-based crop rotations), field vegetables (with cabbage as a model crop), perennial systems (fruit crops and grapevine) and protected crops (with tomato as a model crop). For each selected farming system, existing methods were combined with new tools and technologies into novel IPM solutions combining tactical (e.g. BCAs, physical control methods) and strategic (e.g. rotations in annual crops) means of controlling pests, and addressing the biological, agronomical, and economical diversity in Europe. To study their suitability for trials, they were ex-ante assessed using DEXiPM, a multi-criteria sustainability evaluation tool introduced by ENDURE and adapted by PURE to all the farming systems studied. Then, they were tested on-station and on-farm under the agro-ecosystems and farming conditions of the main broad European regions and subject to a comparative ex-post assessment using a set of methods developed/adapted within PURE: adapted ex-post versions of DEXiPM, cost-benefit analyses, and a model of environmental risks, SYNOPS-WEB. Generally, IPM solutions showed higher or similar overall sustainability compared to current practice and significant environmental benefits but a lower economic sustainability in several cases. Subsidising farmers implementing IPM could remove the economic constraints.

As interactions with key stakeholders are important in the process of designing and implementing IPM, a part of the project studied co-innovation processes in pilots (groups of farmers plus advisors and researchers) in selected case studies for wheat and vegetables. The pilots resulted in clear changes in the farming practice and in the advisor role.

In addition to the assessment tools mentioned above, PURE provided several modelling tools to help identify IPM solutions in the near future: three platforms, to design ecological models, to predict injury profiles, and to model yield losses caused by an injury profile, respectively; optimisation tools; a chain risk-economic model applied to fruit crops; models for optimal plant genotype and genotype
deployment in space and time for yellow rust; a model of multiple weed genotypes; a generic model of pest population and natural enemies in landscapes for the deployment of control measures.

PURE also provided scientific knowledge to design future solutions, based on innovative research in challenging fields. Key outcomes were:

- Model-based or experimentally-based novel strategies for durable plant resistance, for replacement of reliance on herbicides by integrated options, and for durable efficacy of biocontrol agents (BCAs);
- Evaluation of combinations of defence- and priming-inducing agents to enhance the plant defence; production methods or substrates for BCA for pathogens, morphological and DNA characterisation and rearing regimes for enemies of insect pests; characterisation of promising biopesticides;
- Knowledge on (i) the effect of soil management practices on soil disease suppression mechanisms; (ii) the response of natural enemies to habitat amendment strategies, however associated to an equivocal response in terms of pest regulation; (iii) multi-scale pest dependence on crop and semi-natural habitat;
- Designed and tested air sampling traps and optical methods for macro-scale mapping of diseases; optimized PCR methods for quantification of fungal species; tested prototypes for decision-making (weed control), for control tactics (pheromone dispensers, vibration mating disruption system) and precision spraying.

Overall, the diversity of PURE outcomes will contribute to reducing the reliance of European farming systems on pesticides and to facilitate the implementation of the pesticides package legislation.

Project Context and Objectives:
European agriculture is facing two main challenges: increase the food production and quality of products and decrease its environmental impacts. Ensuring sustainability and competitiveness with reduced pesticide inputs is a major objective to be met with Integrated Pest Management (IPM), exacerbated with the regulatory context of the “pesticides package” and of the Framework Directive on the sustainable use of pesticides that made the implementation of eight IPM principles in all Member states mandatory since January 2014.

The overall aim of PURE was to build a toolbox of approaches, methods and tools for implementing efficient IPM solutions in this challenging context. To reach this aim, the PURE team defined two major objectives.

A first major objective was to provide IPM solutions, i.e. combinations of tactical and strategic means of controlling pests taking into consideration the whole cropping and farming system. This provision had to be based on design and test in real conditions. The targets of these IPM solutions were key European farming systems (Table 1) in which reduction of pesticide use and better control of pests should have major effects: annual arable farming systems (wheat-based and maize-based crop rotations), field vegetables (with cabbage as a model crop), perennial systems (fruit crops and grapevine) and protected crops (with tomato as a model crop).

The second major objective was to provide scientific knowledge to design future solutions, based on innovative research in challenging fields: emerging technologies, plant-pest-enemies interactions, ecological engineering (soil and landscape ecology) and pest evolution. Various forms of knowledge were expected: innovative diagnostic and decision support systems, physical devices, and bio-products, strategies for ecological pest regulation at the field and landscape levels and improved durability of control methods.

To reach these aims, PURE brought together scientific and methodological approaches and models associating all the actors of pest management in Europe (researchers, companies active in the field of IPM, development and farmers organisations, etc.). It was built in 3 main Pillars as shown in Figure 1, for a total of 14 work packages (WP).

In Pillar 1, WP1 provided a common methodological framework and adapted tools to help WP2 to 7 to design and assess IPM solutions in regard to their agronomic, environmental and socio-economic performances. Major objectives were to adapt DEXiPM, a pivotal multi-criteria assessment tool for ex-ante and ex-post assessment of IPM solutions, to the farming systems studied; to scale up SYNOPS, an ecotoxicological assessment tool; to develop methods for cost-benefit analyses; and to explore the capacities of novel model-related tools to address IPM design in the timeframe of PURE and in the near future. WP2-7 designed and tested IPM solutions for the 6 farming systems of Table 1, under the agro-ecosystems and farming conditions of the main broad European regions, by on-station and on-farm experiments. They performed a comparative assessment of their environmental, economic and social sustainability.

In Pillar 2, WP8 objectives were to provide tools and concepts for using diversification of IPM to counteract the emergence of super strains of diseases, weeds and pests, and mitigate the negative consequences thereof. This implied, on the one hand, developing models for air-borne plant diseases and weed populations evolving towards virulence and fungicide/herbicide resistance and simulating IPM strategies on this basis. On the other hand, this implied analysing the risks of resistance development to biologicals and designing appropriate solutions. WP9 objectives were to take advantage of knowledge on plant-pest-enemies interactions to enhance the natural plant defence by combining defence- and priming-inducing agents, to develop biocontrol strategies for use against plant pathogens and insect pests, and to identify natural products that could function as biopesticides. WP10 objectives were to explore the ecological processes that underpin the response of pests to changes in habitat and to design ecological engineering
strategies based on the management of habitat to achieve pest suppression. The target application areas were the suppression of pathogens by soil microbial communities, the deployment of plant diversity for conservation biocontrol of arthropod pests, and the response of pests to the dynamic habitat mosaic of farmed landscapes. WP11 objectives were to develop new technologies: detection and monitoring methods at the macro-scale level (airborne sampling and optical sensing) and at the micro-scale level (molecular-based diagnostic tools); innovative crop protection methods including a new generation of generic decision engine for weed control, mating disruption devices for pest control, and precise crop protection products application.

In Pillar 3, WP12 aimed at disseminating the project results among the concerned stakeholders groups, using not only direct participatory methods such as local events and congresses, but also digital tools available on the public website of the project, in order to reach a broader audience: virtual farm visits and e-learning material. WP13 implemented a co-innovation approach of IPM design. Its objectives were to develop a generic approach for co-innovation of IPM technology and methods by farmers, advisors, local policy makers and scientists, which included process monitoring capabilities, progress indicators and stakeholder management. This implied implementing and evaluating the approach in a selection of case studies corresponding to WP2-7 activities.

Project Results:

- **WP1 - IPM design and assessment methodology**
  WP1 developed a wide range of approaches for the design and assessment of IPM-based cropping systems. It aimed 2 objectives: i) to support design and performance assessment activities in WP2-7 and ii) to develop generic methodological studies to help design and assess the performances of IPM solutions.

  **Methodological support to WP2**
  WP1 helped structure proper data flow and ensure harmonisation within PURE Pillar 1 (WP2-WP7). Protocols were stored, shared and made available via the QUANTIPEST platform previously developed by ENDURE (http://www6.inra.fr/quantipest). A novel web-based tool for environmental risk assessment of pesticides considering regional environmental and field conditions was developed. SYNOPS, an ecotoxicological risk indicator model for pesticides was used as a basis to develop this tool baptised SYNOPs-WEB (http://sf.jki.bund.de/synops-web). It was applied for ex-ante and ex-post assessment of the newly designed IPM strategies for the different crops in WP2-7. A Cost-Benefit Analysis was conducted to assess the economic performances of the cropping systems tested in WP2-7. In order to do so, a common template was designed and used to perform assessments of economic performances in terms of gross margins. A risk assessment was performed to analyse the probability that the IPM farming practices will achieve different performance levels as a function of economic drivers. DEXIPM platform was adapted for ex-ante multi-criteria assessment of the sustainability of innovative cropping systems designed in WP2-7. It is composed of qualitative aggregative trees associated to utility functions that represent the social, environmental and economic performances of cropping systems. Ex-post assessments are now possible for wheat, maize based cropping systems (WP2 and WP3, work conducted in ENDURE); field vegetables (WP4) and pome fruits (WP5). In order to further analyse drivers of the adoption by farmers of the IPM solutions identified in WP2-7, a review on incentives and policies for Integrated Pest Management in Europe was performed (Lefebvre et al, 2014).

**General methods**

A specific ontology on IPM was developed in collaboration with the VALERIE European project. A generic modelling platform named UNISIM (http://www.ecolmod.org/) was developed in order to help design models for IPM strategies (Holst, 2013). It was used in conjunction with WP8 for modelling weed adaptation to herbicides and with WP1. Task3 for multiple pests modelling (X-PEST applied to wheat). The PREMISE apple scab and PREMISE-insect models were developed in collaboration with WP5 to help manage these pests on apple trees. They use a Chain Risk structure with emphasis on residue requirements from retail, combining population dynamics, economics, environmental risks and human health risks. An offline version of X-PEST was developed under the VLE environment to help design damage models for multiple pests. A X-PEST model dedicated to wheat was designed with UNISIM (Holst, 2013). A generic platform named IPSIM (Aubertot and Robin, 2013) was developed in order to help design qualitative models that represent injury profiles of a given crop in a given production situation as a function of cropping practices, soil, climate and field environment. It was used to develop 8 pest models on wheat (Robin, 2014). Mathematical modelling approaches based on the use of population dynamics models in continuous and/or semi-discrete time permitted i) aggregative optimisation procedure (Grechi et al, 2012); ii) the optimisation of natural enemies introductions; iii) the analysis of food source diversity and classical biological control efficiency using generalist natural enemies; iv) the model plant compensation in plant-insect dynamics (Lebon et al, 2012; Lebon et al, 2014). A Graph-based Markov Decision Process toolbox was developed in Matlab. It provides resolution algorithms for problems of sequential decision under uncertainty in a spatial context (e.g. Tixier et al, 2013), along with a simple example for disease management in a set of fields. An experiment was conducted to analyse consumers’ reaction to the transition towards Integrated Pest Management (IPM) as the standard in European farming (Biguzzi et al, 2014). An experiment on consumers’ willingness to pay was set up for the tomato case study. Results indicated the existence of strong substitution opportunities between IPM and organic tomatoes, whilst substitution with conventional tomatoes appears more limited. Experimental results also indicated that the withdrawal of conventional tomatoes from
shelves due to the implementation of the Sustainable Use of pesticides Directive could benefit organic rather than IPM sales if the price difference between organic and IPM was low, even if organic produces were more expensive. Only a significant reduction in the price of IPM tomatoes, compared to organic and/or an important increase in the shelf space dedicated to IPM, would appear to increase IPM sales. WP1 also contributed to an international short course on modelling for sustainable management of crop health in 2014.

In sum, WP1 permitted significant methodological breakthroughs with regards to: i) the integrated assessment of IPM solutions in terms of social, environmental and economic sustainability; ii) the assessment of ecotoxicological risk of pesticides at various spatial levels (from field to regional levels); iii) multiple pest modelling; iv) epidemiological chain risk modelling; v) generic ecological modelling; vi) optimisation technics; vii) Cost-Benefit Analysis of IPM solutions; viii) analysis of consumer's willingness to pay for IPM-based produced; ix) economical drivers of the adoption of IPM solutions by farmers.

- WP2 – Innovative IPM solutions for winter-wheat based rotations

Innovative IPM strategies in winter wheat based rotations were studied in on-station and on-farm experiments.

On-station experiments
In total 6 multiyear on-station field experiments were conducted comparing the agronomic, economic and environmental performance of current practice (CP) and two IPM strategies (named IPM1 and IPM2, respectively) in winter-wheat based crop rotations. The experiments were conducted in Denmark, France (2 locations), Germany, Poland and Scotland (Figures 2.1 & 2.2). The experiments in Denmark, Germany, Poland and Scotland were initiated as part of PURE and have only run for three years while the two French experiments were on-going experiments designed to study other aspects than IPM implementation. The four experiments in Denmark, Germany, Poland and Scotland were 3-year rotations including only the three strategies. The French experiments had more treatments and current practice and the two IPM strategies were chosen among the treatments. In one of the French experiment advanced IPM was a ‘no pesticide’ scenario while in the other one it was an ‘organic’ scenario. Except for the German trial, crop rotation was part of the IPM strategies.

The main focus of the two IPM strategies was to reduce the dependence on herbicides and fungicides while less focus were devoted to insect pests and thus the use of insecticides as weeds and diseases (Figure 2.3) are generally considered more important than insect pests in winter wheat based rotations in Northern Europe. The current practice represented what could be considered good agricultural practice in the country/region where the experiment was located. Compared to current practice IPM1 had a more diverse crop rotation (winter and spring annual crops), more use of preventive cultural practices, mechanical weed control measures and disease resistant varieties. In IPM2 further crop diversification (perennial crops), cover crops, more use of forecasting models and decision support system and innovative IPM tools such as elicitors was added to the list of IPM tools applied for IPM1.

IPM1 winter wheat yields were either comparable or lower than those of current practice while the IPM2 yields generally were lower than current practice (Figure 2.4). Highest yields were recorded in the UK in 2012/13. Yields losses were highest in the UK and in the French trial where IPM2 resembles an organic scenario (ACTA- Arvalis). In some cases yield losses in IPM1 and IPM2 could most likely be attributed to the applied IPM measures, e.g. delayed sowing (IPM1 and 2 in Denmark in 2012/13), while in other cases it was caused by unsatisfactory pest control (IPM2 in 2011/12 in Denmark). Pesticide use was reduced significantly in the two IPM systems compared to CP (Figure 2.5).

The sustainability of the 3 systems was assessed using DEXiPM. The overall sustainability of a system was the weighted average of the economic, environmental and social sustainability. The economic sustainability was estimated on basis of a cost-benefit analysis while the environmental sustainability to a great extend was determined by the output of a pesticide risk analysis using the SYNOPS model. The results of the DEXiPM analyses are shown in Table 2.1.

The outcome of the DEXiPM analyses varied between locations. In Denmark and France (Arvalis) the highest overall sustainability was achieved with IPM1 while no differences were observed at the other locations. While the economic sustainability of CP and IPM1 was comparable at most sites the IPM2 system performed poorly. On the other hand the environmental sustainability of the IPM2 system was generally better than that of the two other systems.

On-farm experiments
On-farm experiments were conducted in Denmark, France and Germany. In the on-farm experiments only winter wheat and not the rotation was targeted.

In the Danish on-farm experiments current practice was compared to two IPM strategies (IPM1 and IPM2) using disease resistant winter wheat varieties or mixtures of cultivars and reduced pesticide doses. Pesticide use expressed as the TFI was reduced by 59 and
The experiments were conducted in Italy, Germany, France, Hungary and Slovenia. Additionally, in Italy and Slovenia, the need of Hungary (2013-2014), France and Slovenia no treatment was done. control in the conventional treatment was only done in Italy and Hungary (only 2011-2012) by spraying a broad spectrum insecticide. In were done except for the experiments in Italy where a hoeing was done to incorporate the urea fertiliser being a common practice. ECB machinery in the region. In the conventional tool (CON), weed control was done by a broadcast spraying, no mechanical operations and ECB control (biological treatment by T. brassicae or B. thuringiensis). The tested tools had to be applicable with the available In the on-farm experiments, separate IPM tools were tested for weed control (combinations of chemical and mechanical weed control) and ECB control (biological treatment by T. brassicae or B. thuringiensis). The tested tools had to be applicable with the available machinery in the region. In the conventional tool (CON), weed control was done by a broadcast spraying, no mechanical operations were done except for the experiments in Italy where a hoeing was done to incorporate the urea fertiliser being a common practice. ECB control in the conventional treatment was only done in Italy and Hungary (only 2011-2012) by spraying a broad spectrum insecticide. In Hungary (2013-2014), France and Slovenia no treatment was done. 

68% adopting IPM1 and IPM2, respectively. Gross margin was highest for IPM2 while current practice and IPM2 were comparable despite a lower yield in IPM2 (10.39 and 9.56 t/ha, respectively).
In the French trials current practice was compared to either one or two IPM strategies. Nitrogen use was reduced in the IPM strategies to minimise disease problems and reduce the need for growth regulation and consequently only fungicide and plant growth regulator use was reduced in the IPM strategies while the use of herbicides and insecticides were the same in all strategies. Gross margin tended to be lower using the IPM strategies due to lower yields. Environmental benefits of adopting IPM were generally low and this could be related to the fact that herbicide and insecticide use was the same as in the current practice. Insecticides are the main cause of effects on aquatic organisms while risk to groundwater is primarily caused by herbicides.

In Germany field demonstrations experiments in winter wheat were carried out in close collaboration with the Plant Advisory Service on five farms in Northern Germany. The main objective was to achieve a reduction of TFI based on the choice of resistant varieties, weed identification, intense disease monitoring efforts and the strict application of decision support tools (thresholds etc.). The DSS herbicide tool was used for decision support to weed control and warning services were used for disease control. Three strategies corresponding to current practice, IPM1 and IPM2 were compared. One main focus was to scrutinize the effects of a reduction of the TFI in winter wheat within the modification of the cropping systems. The doses of herbicides and fungicides were planned to be reduced 30%, 50% and 66% in the three systems, respectively. The doses of insecticides were not reduced in current practice and IPM1 and by 25% in IPM2. The average TFI's in the period 2012-14 were 6.3 3.5 and 2.3. Significant winter wheat yield losses were observed for IPM2 (7.06 t/ha) while yields for current practice and IPM1 were comparable (8.13 and 7.6 t/ha).

- WP3 - Innovative IPM solutions for maize-based cropping systems
Based on the results of the experiments (on-station and on-farm, 2011-2014) the sustainability of the tested IPM tools and strategies implemented in grain maize based systems was compared with the current conventional approach. Important aspects taken into account were the agronomic sustainability as well as the economy (total variable costs and gross margin) and the environmental impact (risks for aquatic and terrestrial life assessed with the model SYNOPS). IPM tools and strategies were tested against weeds and the European corn borer (ECB), a major pest in most European regions (Figure 3.1).

On-station experiments
In the on-station experiments two multi-pest IPM strategies (packages of measures) were compared with the conventional strategy, the latter being the current farmers’ practice in the region. In the 1st IPM strategy (advanced), crop rotation was more diversified (grain maize is substituted partly by soybean or peas) and crop management measures were relatively close to current practices (e.g. cultivar choice, combination of chemical and mechanical weed control, using selective pesticides for ECB control, soil pesticides only applied when indicated by monitoring) but with a caution use of pesticides. In the 2nd IPM strategy (innovative), crop rotation was extended with cover crops (only Italy), more innovative measures (e.g. biological ECB control) and the use of pesticides was reduced to the minimum possible. The experiments were conducted in Italy, Hungary and France. It should be emphasized that in Italy and Hungary not all crops were present each year. This means that for these countries the effects of IPM level can also be affected by differences in climatic conditions between the years.

The sustainability of the tested systems in the on-station experiments was evaluated with the model DEXIPM for arable cropping systems, a tool for the qualitative multi-criteria sustainability assessment of cropping systems. For Italy and France the overall sustainability of the IPM systems was higher than for the conventional system while for Hungary it was the same for all three systems (Table 3.1).

Generally, the IPM systems improved the environmental sustainability due to a lower use of pesticides and more diverse crop rotations. In the IPM systems the economic sustainability increased in Italy (for both the advanced and innovative systems) while it decreased for Hungary (advance and innovative systems) and France (innovative system). This is due to a lower gross margin of soybean/peas as compared to grain maize production and to the lower crop yields of especially maize in the Advanced and Innovative strategy. The social sustainability was improved in Hungary and France while in Italy it was not affected by the IPM system.

On-farm experiments
In the on-farm experiments, separate IPM tools were tested for weed control (combinations of chemical and mechanical weed control) and ECB control (biological treatment by T. brassicae or B. thuringiensis). The tested tools had to be applicable with the available machinery in the region. The conventional tool (CON), weed control was done by a broadcast spraying, no mechanical operations were done except for the experiments in Italy where a hoeing was done to incorporate the urea fertiliser being a common practice. ECB control in the conventional treatment was only done in Italy and Hungary (only 2011-2012) by spraying a broad spectrum insecticide. In Hungary (2013-2014), France and Slovenia no treatment was done.
The experiments were conducted in Italy, Germany, France, Hungary and Slovenia. Additionally, in Italy and Slovenia, the need of
chemical treatment against soil pests (granule applied at sowing in Italy, seed dressing in Slovenia) was tested.

Weed control
Cost-benefit analysis
The difference in total variable costs between the IPM and conventional strategy ranged from -€80 to +€30/ha (Figure 3.2; left). Averaged over all tested tools the difference in costs was -€5/ha.
The difference in gross margin between the IPM and conventional strategy ranged from -€105 to +€60 €/ha (Figure 3.2; right). Averaged over all tested tools difference in gross margin was -€30/ha.
Although in a part of the experiments (Germany, Slovenia) the efficacy of the tested IPM-tools was lower than in the CON treatment (mainly due to unfavourable weather conditions not allowing timely hoeing operations) no significant differences in yield between CON and IPM were observed.

Environmental risks
In all countries in the CON treatment the risks for terrestrial life are already low to very low. In contrary, the risks for aquatic life are high across all countries. The tested IPM tools decreased this risk to a lower level mainly due to decreased herbicide inputs (Table 3.2).

ECB control
Cost-benefit analysis
The difference in total variable costs between the IPM and conventional strategy ranged between +€5 to +€140/ha (averaged over all tested systems +€70/ha). If only the trials, in which a pesticide spraying was done in the CON treatment (Italy: all years; Hungary: 2011 and 2012), were taken into account on average the total costs increase was +35/ha (Figure 3.3; left).
The difference in gross margin between IPM and conventional strategy ranged from -€155 to +€85 €/ha (averaged over all tested tools -€55/ha). For the trials with a pesticide spraying in the CON treatment on average the gross margin decreased €35/ha (Figure 3.3; right).
No significant differences in crop damage between both IPM tools and CON treatment (insecticide spraying in Italy and Hungary and no treatment in the other countries) were observed and grain yield was also comparable. However, it has to be emphasized that in general economic thresholds for ECB pressure were not exceeded making it difficult to evaluate the efficacy of the tested biological tools.

Environmental effects
Since only biological agents were used in the IPM tools the environmental risks were strongly decreased compared to a situation in which a conventional spraying is done.

Soil pests control
In the experiments in Italy and in a part of the experiments in Slovenia, the effect of chemical treatment against soil pests was also tested. These plots were not included in the cost-benefit analysis, however, soil insecticide application never increased yield. Therefore, it can be concluded that the implementation of IPM principle (no treatment when the pest is below the threshold) will result in a decrease of costs and improvement of the gross margin, as well as in a decrease of environmental risks.

WP3 also conducted on-station experiments in Italy (CNR), Germany (JKI) and Slovenia (KIS) in 2011 and 2012 to provide data for the construction of a Decision Support System (DSS) for weed control in maize (see WP11). In 2013 and 2014 experiments were done to validate the DSS prototype constructed by WP11 for the different countries. Collaboration between WPs and results were satisfactory.

• WP4 – IPM solutions for important field vegetable crops
On cabbage crops several different pest species and weeds request an intensive plant protection.
In Denmark and the Netherlands mechanical weed control methods (robotic weeding (Fig. 4.1, 4.2) harrowing, finger-weeding (Fig. 4.3)) were compared with chemical weed control.

Results showed that both intelligent (robotic weeding) as well as non-intelligent mechanical weeding performed nearly equal. Mechanical weeding is a very good alternative for chemical weed control (Fig. 4.4, 4.5). However, success is dependent on weather conditions since wet weather conditions lead to unsatisfactory weed control. Apart from weather circumstances, proper adjustment of the machinery has great impact on the weed control effect.

Another focus in WP4 was laid on insect pests, such as cabbage root fly (Delia radicum) (Fig. 4.7) aphids (Brevicoryne brassicae) and caterpillars (mainly cabbage moth (Mamestra brassicae), cabbage white butterfly (Pieris rapae) and diamond back moth (Plutella...
The cabbage root fly is a major pest of Brassica crops. Control is difficult and only few insecticides are authorized. Especially in organic production alternatives for cabbage root fly control are urgently needed. Different alternative plant protection products, such as entomopathogenic fungi and nematodes, nitrogen lime, methyl jasmonate were tested. Best control of cabbage root fly was achieved when plants were drenched with spinosad before transplanting (Fig. 4.8 Fig. 4.9). Spinosead is a natural product which is produced by the soil bacterium Saccharopolyspora spinosa and is listed for use in organic production according to EU-standards. Entomopathogenic nematodes (Steinernema feltiae) and predatory mites (Macrocheles robustulus) as a combination reduced pupae slightly but not consistent. In addition those products are still rather expensive. More pupae were found on plants treated with nitrogen lime (Fig. 4.9). Current recommendation to farmers is the drench of plants with spinosead shortly before planting which reduce the amount of pesticide to a minimum in comparison to a full area field application. More research is needed to find alternative products for cabbage root fly control, as there is on one hand the risk of fast resistance development when control is based only on one substance and on the other hand the lack of products against adults for direct sown Brassica crops. Furthermore cabbage root fly behavior towards volatile compounds was investigated and ecological processes with push-pull strategies exploited. EthoVision® bioassay results revealed that newly hatched cabbage root fly larvae were significantly attracted to host plant root volatiles. Dimethyl disulfide was attractive to larvae, but toxic at the highest dose tested. In field experiments dimethyl disulfide was confirmed as a compound strongly decreasing oviposition in a target crop (i.e. broccoli) while hexenyl acetate increased this oviposition in a trap crop (i.e. Chinese cabbage).

To control aphids and caterpillars broad spectrum insecticides were compared with selective insecticides and biological ones. Plants were treated fortnightly when control thresholds for aphids or caterpillars were exceeded, respectively. Based on regular monitoring control of insect pests after control thresholds are exceeded is a successful tool in reducing insecticide applications. Results showed that biological (Bacillus thuringiensis against caterpillars and rape oil against aphids) and selective insecticides (indoxacarb against caterpillars and pirimicarb against aphids) performed as well as broad spectrum insecticides (Fig. 4.10). Since farm conditions and market requirements are very diverse, thresholds need to be adapted to the particular farm conditions and production aims. Furthermore the development of control thresholds for other pests, such as thrips and swede midge, is essential to offer IPM for the whole pest system.

- WP5 – Innovative IPM pome fruit systems

Climatic conditions in Europe are favourable in many apple producing regions for disease development by apple scab caused by the fungus Venturia inaequalis (Fig 5.1). In susceptible apple cultivars yield loss can range between 40-70%. Even in Hungary, apple scab control traditionally needs 12-20 chemical sprays annually. Innovative control options were tested in order to reduce inoculum sources of apple scab and if possible to reduce the number of chemical sprays against the disease.

Small scale on-station and large scale on-farm experiments were conducted comparing three protection strategies:

- Standard: spray with fungicides and insecticides and the use of warning systems;
- IPM1: leaf removal + fungicide + insecticide sprays with mating disruption;
- IPM2: leaf removal + pruning + insecticide sprays with mating disruption using mainly granulosis viruses, Bt.

On-station treatments were done in 5 replicates with 10 trees per replicate, assessment on middle 6 trees. While the on-farm treatments were replicated three times of each field 0.5 ha, assessment within each replicate 5 replicates of 6 trees. For both on-station and on-farm, fruit and leaf scab were assessed. Assessment was made on 6 x 200 leaves and 6 x 25 fruits /replicate.

Results from the on-station experiment showed that scab leaf and fruit incidences were the highest in the most innovative systems of IPM2. Yield was the highest in standard and IPM1 systems. Fruit grading class I was the highest in IPM1. Thus, the on-station experiments showed that strongly reducing fungicides from the IPM1 schedule in the IPM2 system resulted in higher amounts of apple scab incidence. Results from on-farm experiment supported results of the on-station experiments. Leaf and fruit incidences were the highest in the most innovative systems of IPM2 with 16.5% and 9.9% for leaf and fruit scab incidence, respectively. Yield was the highest in standard and IPM1 systems. Fruit grading class I apple was the highest in IPM1 and standard systems with 21 tons/ha out of the total of 31tons/ha. Overall, IPM1 strategy was the best for scab control and yield aspect with autumn leaf removal in order to reduce primary inoculums of the disease. The results from advanced IPM sanitation solutions against apple scab are ready to be integrated by apple growers. They can be implemented in both integrated and organic orchards.

On apple, substantial progress was made in bio-product development based on the biological control agent (BCA) Cladosporium cladosporioides H39 by WP 9 “Plant-pest-enemies interactions”. Different formulations of this product from WP 9, task 2, were tested on field efficacy in commercial organic orchards in our WP5. On-station testing resulted in interest from growers and companies to use...
this BCA in IPM apple production. The BCA C. cladosporioides H39 was successful in organic orchard systems. Different formulations of the BCA and cost-effectiveness of the sanitation practices showed good results and will be further studied.

Apple trees require the application of 7-15 insecticides specifically targeting the codling moth (Cydia pomonella) in southern France (Fig. 5.2).

Exclusion netting, as a physical control tool, prevents this pest to reach the trees and potentially replaces all the treatments against this key-pest. There are two forms for this netting, either "a single-row” system (net covers each row) and the “whole-orchard” system (a modification of the anti-hail system). The integration of such innovative IPM tools into advanced fruit production strategies was evaluated. Effects of whole orchards covered with single-row nets were studied under different management strategies in research station experiments on the orchard microclimate, the agronomic performances and the pest complex, such as the fruit damage and infestation levels, and including the rosy apple aphid (Dysaphis plantaginea). These on-farm experiments were conducted in the "Alt’Carpo" network composed of 17 netted and 13 uncovered commercial apple orchards under either organic or IPM management. In on-station experiments, no significant modification of the tree growth or architecture, neither of fruit quality and orchard yield was observed. Harvest date was delayed of a few days under nets, most probably because the climate under nets was significantly but little modified with for example a slight decrease in photosynthesis active radiation. The mean number of rosy apple aphids was higher under the nets probably because some natural enemies such as Coccinellidae could not reach the aphid colonies. Conversely, codling moth and other Lepidoptera, e.g. fruit Tortricidae were highly controlled and consequently the percentage of damaged fruit was close to zero.

In conclusion, under the French on-farm network, the ‘single-row' netting system enabled a significant reduction in pesticide use without any major risks for the production. Insecticide use was reduced from 13.7 equivalent full-dose treatments down to 4.1 with net, while fungicide use remained similar, 13.4 treatments without versus 14.8 with net.

To design advanced IPM in pear orchards for disease control is based on the integration of degradation of the leaf litter where the pathogen overwinters and sporulates to reduce the inoculum, provided by biocontrol agents, and the reduction of the number of treatments by Decision Support System (DSS) for scheduling fungicide applications. Focus is on enhancement of leaf litter degradation for brown spot disease management on pear (Stemphylium vesicarium), being the most severe disease in southern Europe in pear cultivation (Fig. 5.3).

Experiments with different combinations of vinasse (= borlanda), Sordaria fimbriata and Trichoderma sp. were tested on cv. Conference leaf litter. Leaf litter samples were treated at the end of the winter and the amount of leaf residues and the speed of degradation were assessed at regular intervals by means of image analysis software until early August. The application of Sordaria sp. caused a quicker and higher degradation of the leaf residues compared to untreated control. This result is relevant in order to reduce the inoculum of S. vesicarium during winter time. In on-farm experiments, two systems were compared: i) a standard system, representing the average of a large production area in North Italy, and ii) an innovative IPM system where the use of a DSS for scheduling fungicide applications was combined with leaf litter removal and periodical applications of the BCA Sordaria sp., commercial formulates of vinasse and Trichoderma spp. The experiments were replicated in 2013 and 2014 on cv. Conference and Abate-Fetel, both very susceptible to brown spot. The results were promising because the disease was similar in the IPM system and in the standard, but there was a 50% reduction in terms of pesticide usage. The impact expected is a general reduction of the overwintering inoculum of the pathogen, which plays an important role into the epidemic development of the disease.

Another PURE purpose is to assemble an IPM strategy for all pests of pear with only harmless pesticides for natural enemies of pests and non-chemical methods. Emphasis was on the pest pear psylla (Fig. 5.4).

Negative side effects were investigated on the natural enemy common earwig (Forficula auricularia), one of the important natural enemies of pear psylla. Exposure to pesticide residues on bean leaves showed that none of the fungicides and leaf fertilisers had negative side effects on common earwig (Forficula auricularia). However, some insecticides such as indoxacarb, neonicotinoids and pyrethroids had negative side effects on earwigs. And female earwig exposed to residue of the herbicide amitrol deposited eggs, but these eggs died and no offspring was produced. Through regular winter meetings of fruit growers, advisors and pesticide merchants, the sustainable control of pear psylla in an all-pests strategy is promoted and discussed. Results showed that yield quantity was not affected by the selective pesticide schedule compared to the commonly used pesticide schedule which still contains pesticides with negative effects on predators. Growers did not notice any difference in yield quality either. Commercial growers present their experiences with the strategy and by that more growers are convinced to follow the strategy. Both for fruit growers and chemical industries awareness of the importance of natural enemies for sustainable pear productions is growing.

Statistical information was collected on fruit prices in higher market segments. The export data, volumes and values from Eurostat and processed by LEI Wageningen UR showed price premiums for apples and pears when exported to high market segments. Producer
organisations and trade companies can use these data for developing new business models. The information can promote implementation of IPM in practice. Further research on the product and quality requirements of high market segments is needed to complement the price information.

- **WP6 – IPM solutions to reduce pesticides reliance in grapevine**
The aim of Work Package 6 was to develop innovative integrated pest management (IPM) methods for grapevine and to stimulate the uptake of these methods into practice. More specifically, the objectives were:
  - To produce IPM solutions that address the most critical pest problems in European grapevine systems
  - To test candidate IPM solutions in on-station and on-farm experiments
  - To assess and compare field-tested candidate IPM solutions using multiple criteria and endorse viable solutions for mainstream dissemination
  - To stimulate and promote uptake of innovative IPM methods into practice.

An initial survey identified the most important pests and diseases of grapevine in terms of pesticide input and risk of losses in the different regions of Europe. A database on the possible IPM tools based on the existing literature and availability of commercial alternatives to pesticides was built and continuously updated. The IPM tools of the database were used to design the IPM solutions that have been ex-ante evaluated with stakeholders. On-farm and on-station experiments were carried out on the identified main pests and pathogens.

In the WP6 we tested innovative control methods and IPM solutions against Botrytis cinerea (grey mould), Erysiphe necator (powdery mildew), Plasmopara viticola (downy mildew), Lobesia botrana (European Grapevine Moth) and Planococcus spp. (Fig. 6.1).

Tested IPM solutions and innovative control methods are based on decision support systems (DSSs), combination of microbial biocontrol agents (biopesticides), reduction of the overwintering inoculum of the diseases, agronomic practices and resistant varieties. In term of cropping system design and experiments the results are:
  - the design of various prototypes of grapevine cropping systems with a significant reduction of pesticide use (over 50%), integrating a set of coherent techniques contributing to the regulation of pests and diseases.
  - confirmation of their performances and sustainability within a network of experimental stations located in 3 contrasted regions of France.

Against B. cinerea a strategy based on three microbial biocontrol agents having different mechanisms of action applied in those specific phenological stages of grapevine when their specific activity is maximised, was found to be effective in all the tested environment. Agronomic measures based on summer pruning and defoliation around bunches, was experimented and was confirmed to be effective.

Against E. necator, a biological method based on application of a hyperparastite (Ampelomyces quisqualis; commercial product AQ10) to reduce overwintering powdery mildew inoculum (chasmothecia), was found to be effective only in warmer and Mediterranean climate.

Against insects the IPM solutions and related results are:
  - identification of alternatives to chemical pesticides in controlling grape berry moths in area where mating disruption is not practicable, in these alternatives biological insecticides were found to be effective.
  - Evaluation of the effects of natural pesticides (e.g. microbial and botanical pesticides) towards other pests and key-beneficials occurring in vineyards were tested, and promising results with these solutions have been achieved.

Decision Support Systems for scheduling fungicide applications against downy and powdery mildews in different grape-growing area of EU were developed in order to reach the objective in term of reduction of pesticides by optimising application.

- **WP7 – IPM solutions for protected vegetables**
As IPM was already partly used in Northern-Europe greenhouse productions at the beginning of the PURE project, the overall objective of the WP7 workpackage was threefold: implementing IPM in Southern Europe, promoting "real IPM" based on biological control rather than "Integrated Pesticide management", and enhancing the reliability of these strategies with regards to climate change disturbances. To accurately assess the situation and developments in the greenhouse tomato sector, and the marketing of tomatoes in Europe, two surveys have been performed in 2011 and 2014 in relation to crop protection and in interaction with stakeholders. Focal points of this investigation were sector structure (acreage, farms and regions), greenhouses and technology, growing periods and tomato types, exports and market prices, main pests and diseases and main control methods. Based on this information, we designed IPM solutions adapted for different levels of greenhouse technology and combining strategic options and tactic components.
At the end of the program, more robust IPM solutions have been validated, specifically adapted to local socio-economic constraints and to a large range of greenhouse farming systems including low-tech greenhouse crops that are the most represented in Southern-Europe. These more robust solutions include a large range of tools based on stable, efficient and complementary biological control agent associations targeted to multi-pest control issues and crucial knowledge on synergistic properties and/or incompatibilities among these IPM tools.

The keystone of our strategy has been to emphasize the use of polyphagous predators able to control the main pests present in greenhouse systems. It has been demonstrated that the IPM solutions based on the use of the mirid bug predators, Macrolophus pygmaeus and Nesidiocoris tenuis minimize the use of pesticides in inducing a very effective control of tomato key pests: the whiteflies Bemisia tabaci and Trialeurodes vaporariorum (Westwood) (Fig. 7.1) and the very dangerous invasive moth Tuta absoluta (Fig. 7.2).

Within this framework, several advanced protocols of release for these predators have been validated in order to establish them at very early stages of the crop cycling (pre-transplanting in nursery) when the pest pressure is very high. The second objective was to favour a long-term establishment with the supply of alternative food in the crop and good results have been obtained with Ephestia kuehniella eggs and Artemia cysts.

This polyphagous predator strategy has also been improved by combining it with three complementary biocontrol solutions:

- In South Italy, an IPM strategy based on the use of the sexual pheromone of Tuta absoluta was also used. The mating disruption technique was applied by distributing inside the greenhouse dispensers emitting the sexual pheromone at high density. This strategy allowed for important chemical spraying savings: from 9 chemical sprayings in the conventional strategy to none.
- In South France, a Macrolophus pygmaeus strategy was combined with a release strategy using the parasitoid Trichogramma achaea to control T. absoluta. This strategy successfully worked since no chemical treatments were done as the pest pressure was very high. In this case, the combined strategy performed much better than the mirid strategy alone (30 to 12% and 15 to 0% reduction of fruit bored).
- In South France, biocontrol plants (banker plants, in this case) were used to increase the populations of the predatory mirid bug (Macrolophus pygmaeus) to control whiteflies (Trialeurodes vaporariorum). The results ranged from efficient banker plant (tobacco) to not recommended (Dittrichia viscosa) through indifferent or neutral (basil). In the case of tobacco, it also appeared to be efficient as banker plant for whiteflies. Consequently, none of the banker plants tested are recommended to increase M. pygmaeus populations in the presence of whiteflies (T. vaporariorum).

Success of polyphagous predator strategy in combination or not with mating disruption, parasitoid release and biocontrol plants has minimised the use of pesticides in tomato and the specific treatments conducted are currently mainly targeted to control Aculops lycopersici with selective acaricides. The incidence of the tomato yellow leaf-curl viruses (TYLCV and TYLCSV), which were the limiting factors to cultivate tomatoes in the past, has also decreased significantly since the use of this predator against B. tabaci has become widespread and probably also thanks to the use of tolerant tomato cultivars.

Along with pest control, a huge effort has been performed to control tomato pathogens in clay soil culture in the frame of PURE WP7. By on-station and on-farm trials, we demonstrated that the use of selected microorganisms and their metabolite is a strategy successfully applicable for the control of soil-borne pathogens Fusarium oxysporum, Pythium ultimum, Sclerotinia sclerotiorum, Rhizoctonia solani. Our approach included the use of biological control agents and their products as alternatives to synthetic agrochemicals. Trichoderma spp. were selected as there are the most commonly used microbial biological control agents (MBCAs) in agriculture. The efficacy of this fungus can be attributed to its ability to produce the conidia, enhance vegetative growth and contain pathogen populations under numerous agricultural conditions. Results obtained demonstrated that all the applied Trichoderma strains can be used as an alternative to Previcur to control natural occurring soil-borne pathogens. Results of experiments with microorganisms indicate that the use of microorganisms and their metabolites is an added value for IPM of tomato cultivation.

Within PURE WP7, a particular attention was paid to indirect effects of the promoted biocontrol solutions. Both mirid and beneficial microbial agent solutions appeared also to be of greater added value thanks to their indirect effects on the plant fitness, in terms of signalling, induction of systemic resistance and plant growth promotion that can make tomato crop more robust against new invasive pests and pathogens with regard to global climate change.

As a matter of fact, the use of beneficial microbial agents and of mycorrhizae was also desirable because of in tomato plants they can significantly increase resistance toward insects (aphids), activating both direct and indirect defense mechanisms. Indeed, we also demonstrated that the application of the MK1 strain of T. longibrachiatum to tomato affects the performance of Macrosiphum euphorbiae and its natural antagonists. In fact, when compared with the un-colonised controls, plants whose roots were colonised by T. longibrachiatum MK1 showed quantitative differences in the release of specific volatile organic compounds (VOC), and although the aphid population growth indices are slightly higher, the attractiveness toward aphid parasitoids and predators and the development rate of an aphid predator greatly increase.
Similar results were obtained with mirids which are able to feed on prey and plants during the same developmental stage. By feeding on plants, mirid predators can activate the same defense mechanisms as strict herbivores. The feeding activity of N. tenuis activates abscisic acid (ABA) and jasmonate acid (JA) pathways in tomato plants, which makes them less attractive to B. tabaci and more attractive to the whitefly parasitoid Encarsia formosa respectively. In addition, herbivore induces plant volatiles (HIPVs) from N. tenuis-damaged plants can induce plant defenses in neighboring, undamaged plants via JA, resulting in attraction of parasitoids. These results might be one reasonable explanation for the great success achieved by mirids as a key biocontrol agent in tomato cultivation. To conclude, this advanced IPM strategy, looking for long-term establishment of generalist beneficials, allows the agro-ecosystem to respond quickly to disturbances induced by a large panel of pests and diseases. This includes potentially emerging or re-emerging pest invasions as well as periodic massive entries or endemic explosions of many major pests present within European regions. More generally, we assume that this strategy constitutes a very promising approach with the goal to reduce the magnitude and duration of further biological disturbances caused by climate change.

- WP8 – Pest evolution and enhancement of the durability of IPM solutions

WP8 objectives were to provide tools and concepts for using diversification of IPM to counteract the emergence of super strains of diseases, weeds and pests, and mitigate the negative consequences thereof.

This workpackage had three tasks: (i) Development of strategies ('blueprints') for sustainable use of variety resistance to plant pathogens, (ii) development of strategies for suppressing populations of herbicide resistant weeds in wheat- and maize-based cropping systems, and (iii) development of strategies for addressing resistance development to biological control.

The main activity in task 1 was the construction of multi-scale models for evaluation of the effectiveness of spatial, temporal and genetic diversification strategies to prolong the useful life of plant resistance against plant pathogens, possibly in combination with fungicides. Models for gene deployment in space and time were parameterised with empirical data for yellow rust, Puccinia striiformis forma specialis striiformis, the pathogen with the best data availability. Two models were constructed. The first was at the regional scale and spatially implicit. The second model was at a national scale for France and spatially explicit. With these models, blueprints for sustainable use of plant resistance were developed (D8.2). The models were used to study scenarios for using resistance genes in cultivars taking into account the usage of these cultivars in space and time. We found that overall durability is low and deployment strategy has no effect on the durability when the resistance breaking pathogen phenotype is already present in a minute fraction of the population. If the resistance breaking pathogen genotype has to emerge by mutation, then the useful life of a resistance gene is longer and stacking two new resistance genes in one variety can even have a durable life of more than 30 years. However, if a stacked variety is deployed together with single-gene resistant varieties with the same resistance genes, these single-gene resistant varieties act as stepping stones for the emergence of a resistance breaking pathogen genotype that can break down both resistance genes in the stacked variety, which drastically reduces the durability of the stacked variety. From durability perspective it is desirable to stack two new resistance genes (i.e. resistance genes for which no resistance breaking genotype is present in the pathogen population) in one variety and not use the genes in a single-gene resistant variety. Historic invasions of new rust genotypes in France were analysed using the spatially explicit model.

The second important activity in task 1 was further collection of data on strain identity of yellow rust genotypes in different European countries (focus on Denmark, France and Germany). Since 2011, epidemics of yellow rust in Europe have been caused by new races of exotic origin. Therefore, additional samples from Spain, Portugal, Czech Republic, Slovakia, Poland and Belgium were investigated. Yellow rust data were assembled in an international database (www.wheatrust.org). Furthermore, work was done to characterise genetic variability and host plant relationships in Zymoseptoria tritici. The modelling task was built on this empirical data collection.

Fungicides are in many cropping systems indispensable management tools farmers. Sustainable and durable usage of fungicides, and integration with disease resistance, was studied, focusing on the control of Zymoseptoria tritici. Work was also considering the effect of seed treatment with fungicides on pathogen resistance development. Analyses were conducted to enhance knowledge on genetic diversity and pathogen-host relationship in Zymoseptoria tritici.

Task 8.2 concentrated on the sustainable management of weeds in maize- and wheat-based rotations. Its focus was on evolutionary processes in weed communities in crop rotations to identify weed management strategies that support the preservation of balanced weed floras and avoid selection and evolution towards communities consisting of few dominant species and/or biotypes that are highly competitive and difficult to control. The work had a modelling component as well as empirical data collection on fitness parameters of herbicide resistant and herbicide susceptible biotypes of two principal weeds in cropping systems with wheat (blackgrass: Alopecurus myosuroides) and maize (barnyard grass: Echinochloa crus-galli). Data were collected on the competitive
fitness of herbicide-resistant and susceptible biotypes of these two weed species. Empirical data collection covered the four years of the project, while the modelling effort was concentrated in the last year, after sufficient data had become available. In blackgrass, differences in fitness between weed biotypes were subtle, including differences in germination success from different soil depths. On the other hand, herbicide resistance-related differences in fitness in barnyard grass were major and concerned growth, development and reproductive output. Modelling elucidated how weed abundance and relative frequency of herbicide resistant biotypes can be mitigated by combining weed control options in an integrated weed management package.

Task 8.3 addressed the development of pest resistance to biological control agents. It focused on two study systems: one with a pathogenic fungus (grey mould, Botrytis cinerea) and its fungal biocontrol agent (Microdochium dimerum) and another with a pest insect (codling moth, Cydia pomonella) and an insect virus (Cydia pomonella granulosis virus; CpGV). Botrytis cinerea is a plant pathogen of wide economic importance in which the first evidence of resistance of a fungal plant pathogen to biocontrol was found, while Cydia pomonella is the first insect in which a field resistance to an insect virus was found. By literature review and meta-analysis, risk factors for resistance development in biologicals were identified. Work with insect viruses gave insight in the spatial distribution of resistance in France, and led to new virus strains that overcome resistance. Moreover, genetic analyses of virus strains provided insight in genetic factors contributing to virulence. A co-evolution method was developed to adapt CpGV to non-permissive (resistant) hosts. Using this method an active isolate on resistant insects was obtained and is now commercialised, as well as a new isolate active on Cydia molesta. A patent application was submitted.

- WP9 – Plant-pest-enemies interactions

Interactions between pests and their host plants and natural enemies were studied in order to find ways of reducing pest and pathogen growth rates. WP9 was designed to provide additional tools to contribute to the IPM toolbox. It was divided into 4 Tasks that addressed the following 4 objectives:
1. Assess the potential of selected combinations of defence- and priming-inducing agents to enhance the effectiveness of natural defence in tomato and wheat (Task 9.1)
2. Develop biocontrol strategies for use against plant pathogens (Task 9.2)
3. Develop biocontrol strategies for use against insect pests (Task 9.3)
4. Identify natural products that could function as biopesticides (Task 9.4)

Natural products with a direct effect against pests/microbes or their pathogenic behaviour as well as those providing indirect defence by attracting natural enemies of pests or priming plant were investigated. Biocontrol agents (BCAs) were evaluated to determine which show the most potential for use in crop protection.

Task 1. Assess the potential of selected combinations of defence- and priming-inducing agents to enhance the effectiveness of natural defence in tomato and wheat

We demonstrated that the effects of chemical defence activators on pathogen resistance depend on the tomato cultivar used. This outcome creates opportunities for tomato breeding programmes to select for genetic traits that increase the resistance response to specific combinations of chemical defence activators, whilst minimizing the costs in terms of plant growth reduction. The most effective plant activators emerging from these trials are β-aminobutiric acid (BABA; Figure 1) and fructose. Fortunately, neither of these needs custom synthesis and are already commercially available. Research on the model plant species Arabidopsis revealed the identity of the receptor protein for BABA. This IBI1 protein was found to control disease resistance and plant growth suppression via separate signalling pathways. Hence, the costs of BABA-induced resistance can be separated genetically from the corresponding costs on plant growth. Subsequent experiments with tomato have revealed that tomato perceives BABA in a mechanistically similar manner as Arabidopsis. Our discovery of the plant receptor of BABA allows for more targeted breeding programmes that specifically aim to increase crop responsiveness of BABA-induced resistance, whilst minimising the concurrent stress response to this chemical.

Task 2. Develop biocontrol strategies for use against plant pathogens

Formulations to improve the longevity of fungal biocontrol agents and more efficacious strains have been developed. A natural occurring hyperparasite, Ampelomyces quisqualis, is considered as one of the best alternatives to chemicals against Erysiphales, the casual agents of powdery mildews that are among the most dangerous plant diseases worldwide. We evaluated the effect of five different substances (Powdery mildew extract, Shrimp Shells powder, Chitosan, Yeast cells and Mushroom powder) on the germination rates of three selected A. quisqualis strains (AQ10, ITA 3, ATCC 200245). Conidial germination and tube elongation of strains were stimulated most strongly by shrimp shells. AQ10 exhibited significantly lower germination rates and less tube elongation in the presence of several substances stimulating conidia, as compared to the strain ITA3. In vivo biocontrol assays after stimulation of conidial spores of A. quisqualis were conducted with cucumber (Podosphaera xanthii), strawberry (Podosphaera aphanis) and grapevine (Erysiphe necator) powdery mildews. Best results were obtained with ITA 3 stimulated by chitoplant, shrimp shell and
mushroom which reduced the infected leaf area on strawberry, grapevine and cucumber (62 to 91% less). Several species of the fungal genus Trichoderma are good antagonists of soil borne diseases; they are competitors for space, nutrients and produce lytic enzymes. Trichoderma are common inhabitants of the soil; however their natural concentration is often too low to provide a sufficient antagonism against soilborne pathogens. We have developed an improved strain, Trichoderma atroviride SC1 and conifer bark formulations that improve its longevity.

Task 3. Develop biocontrol strategies for use against insect pests
We developed methods for molecular and morphological characterisation of natural enemies attacking several groups of pests. These methods have been applied to both parasitoids of tomato leafminer Tuta absoluta and to natural enemies of grapevine mealybugs collected in Europe and North Africa. Biocontrol agents for the invasive insect pest T. absoluta have been identified. Quality control is essential to achieve effective biocontrol because different species of insect parasitoids and predators look similar but have completely different performance in controlling the pest. For example, Trichogramma brassicae sold as T. achaeaé by led to failures of biocontrol programmes. We have established morphological and molecular protocols for species characterisation. For Trichogramma species tested there was agreement of molecular and morphological data indicating that the strain sold by Invivo Group (France) was a true Trichogramma achaeaé. The biological performances (longevity, fecundity, host killing and host feeding) of different strains of T. achaeaé have been assessed in relation to different host eggs, rearing history and different conditioning temperatures. Strain and rearing history play a role in final on the total parasitisation rate of T. achaeaé on different hosts including Tuta absoluta.

Task 4. Identify natural products that could function as biopesticides
Ajuga chamaepeyts extract was tested at Rothamsted and found to have antifeedant activity against diamond back-moth Plutella xylostella and T. absoluta larvae. Mass spectrometry analysis conducted provided evidence that clerodane diterpenoids were present in the A. chamaepeyts extract used in bioassays, and that they are responsible for the observed antifeedant activity. DiCQs and diCT extracted from plants have been shown to act against a wide range of aphid species in studies at INRA. They seem to be inactive towards Coleoptera or Lepidoptera. Further work is required to optimize the formulation and mode of application of diCQs/diCT-based biopesticides, for improving their toxicity in the field, either upon contact (through increased rate of cuticular penetration) or ingestion (through the manufacturing of a systemic product). In studies of biopesticide treatments against mycotoxin production, phenolic acids, in particular caffeoic, chlorogenic and ferulic acid, were found to modulate mycotoxin biosynthesis and fungal development. They appear promising natural molecules to be used as biopesticides. However additional studies are required to optimise their formulation and mode of application to improve their efficacy in field trials. The BX compound identified in this project could play an important role in preventing the accumulation of trichothecenes in wheat grain. Breeding or engineering of wheat with increased levels of benzoxazinoids could provide varieties with increased resistance against trichothecene contamination of grain and lower susceptibility to Fusarium head blight.

• WP10 – Ecological engineering for IPM: from field to landscape
The research conducted by partners within WP10 represents a substantial contribution to the study of Ecological engineering strategies for IPM and how ecological processes may be managed to promote pest suppression. In a multi-scalar approach we identified three aspects from the complex and multi-faceted ecology of pest-crop systems where potential for the development of pest suppression strategies could be identified. These were: the manipulation of soil communities to suppress soil-borne pathogens; the role of conservation habitats in supporting naturally occurring biocontrol agents; and the management of crops and non-crop habitats at the landscape scale to influence pest and natural enemy populations.

In Europe, several long-term experiments aiming to improve soil quality and reduce damage to crops caused by soil-borne pathogens are being carried out. Effects of management practices, addition of organic matter, alternative crop rotations and green manure crops have been detected. However, soil is a highly complex habitat with exceptional microbial diversity, obscuring the mechanisms that link soil management to pathogen suppression so that predictable responses are yet to be identified. To address this, a field experiment was conducted to investigate, in detail, the response of a wide range of soil biota to soil management, including crop rotation, cover cropping, and reduced tillage, as the mechanistic link to the suppression of soil-borne pathogens.

In general, the soil present at the trial site was naturally suppressive against disease and several antagonistic bacteria (Pseudomonas and Lysobacter) were isolated from the soil samples. Despite this, changes in soil communities were observed and an impact on pathogen suppression was measured against 1 of 3 soil-borne pathogens tested. These results show that it is possible through the adoption of common and easy to implement management practices to increase the pathogen suppression of soils. However, the responses across the soil biota were complex and remain difficult to predict, indicating that specific advice on management practices in relation to IPM will depend on the pathogens present in the field and the environmental conditions such as soil type, the interactions with crop rotation and management.

The predation and parasitism of crop pests is thought to be a valuable ecosystem service provided by naturally occurring biocontrol
agents. The potential to enhance pest regulation by conserving populations of natural enemies has been considered for some time and subject to experimental test across a number of crop systems. In reviewing this research we established that, in general, natural enemies respond positively to a wide range of conservation strategies based on crop diversification, habitat supplementation and extensification of crop management. However, the conservation strategies of the types considered are unreliable in terms of natural enemy conservation while, overall, they failed to achieve pest suppression. These findings stress the need to better understand the link between the conservation of natural enemies and the delivery of biocontrol. Many of the conservation biocontrol treatments fail to target specific components of the crop-pest system which may contribute to the shortcomings observed. To address this we aimed to improve the biocontrol potential of field margins for the wheat-oilseed rape rotation; hypothesising that a brassica field margin would improve biodiversity and in-field pest control services in wheat and oilseed crops in a targeted manner by the provision of hosts for brassica specialist natural enemies, in addition to the general provision of pollen and nectar resources. Replicated whole-field scale experiments were carried out at Rothamsted, U.K. and Flakkebjerg, Denmark, over two years. The results did not establish the effectiveness of this targeted approach; the inclusion of brassicas in field margins provided clear benefits for the natural enemies of specialist pests which were enhanced at both sites, but, as with other studies, this did not translate into within-field effects on pest populations. In Britain, the margins had the additional benefit of supporting natural enemies usually associated with oilseed rape at points in the rotation when the crop is absent, potentially leading to a biocontrol benefit in the longer term. In Denmark, natural enemies showed a variable response to margin composition; counter to the response of specialist natural enemies, generalist predators were more abundant in the grass margins when compared to the brassica margins. This coincided with significantly higher predation on artificial caterpillars but not on caged aphid prey which showed no difference between margins.

It is well known that landscape composition and structure affect biodiversity including important functional groups. It follows that managing habitat quality at the landscape scale through the deployment of crops, non-crop habitats and crop/pest management could lead to the creation of pest suppressive landscapes.

In an extensive study of the cereal based cropping system in Scotland, generalist predators were found to respond quite generally to the composition of the landscape. For each of the predatory groups considered (ground beetles, rove beetles and spiders) the benefit of complex landscapes was confirmed but with the additional insight that, for this system, the effect is driven by the amount of broadleaf woodland and heath in the landscape, particularly at larger scales, i.e. 50 and 79 km². Though less consistent, the composition of crops within the landscape also had a significant influence on the predators. For example, an increased abundance of carabids was associated with higher proportions of winter oilseed rape at smaller scales, i.e. 0.79 and 3 km². The abundance and parasitism of codling moth, an important pest of pome fruit, and the abundance of a dominant predatory spider were analysed to assess their dependence on local and landscape characteristics, including crop protection practices. In all cases, accounting for landscape characteristics provided a better understanding of their distribution. For example, the results confirm that abundance of codling moth in an orchard is decreased where pesticide treatments were more intensive in the surrounding landscape. The same pattern was observed in parasitism rates confirming the detrimental, non-target effect of pesticide on the main parasitoid of codling moth. Additional habitat effects were also discovered with lower pest densities in fields protected from the wind by a dense network of hedgerows, perhaps because windbreaks help to contain pesticides within orchards. The landscape drivers were different for the spiders with other semi-natural habitat landscape variables being more important but most notably in orchards not covered by coding moth exclusion nets during the growing season.

Though ecologically quite different from the previous examples, the occurrence of weed species across an area of 140 contiguous fields in a wheat cropping area of central France also showed that factors beyond the managed field had a significant influence. For example, agronomic practices (herbicide application, soil tillage regime, type of rotation) were found to influence weed species at wider temporal (up to 5 years preceding the weed presence) and spatial (at the last the practices in the neighbouring field) scales than previously thought. In considering the impact of connectivity between fields on these results it appears that farmers, by dispersing seeds between their fields, are important in mediating the landscape effects.

By studying the three contrasting cropping systems the overall importance of landscapes in influencing populations of pests and natural enemies is clearly established while in each case, specific aspects of the landscape have been identified that offer a target for the development of future pest suppressive landscapes. Building on these findings, the AgBioscape modelling system was developed and used to simulate a Diabrotica-maize and an aphid–parasitoid–wheat system to assess the potential of alternative approaches to managing landscapes for pest suppression. Predictions from the Diabrotica model indicate that adopting an adaptive rotation control strategy across a landscape using action thresholds will successfully control Diabrotica, including rotation resistant strains. In contrast, the aphid-parasitoid model predicted that the introduction of beneficial habitats, while supporting the parasitoid populations, does not provide effective pest control; a result that is consistent with the experimental conservation biocontrol studies reported above. The model allows alternative approaches to landscape management to be considered; for example, much higher levels of parasitism were supported when increased parasitoid survival on crop habitats was simulated, suggesting that measures to supplement crops with food resources may be a more effective conservation biocontrol strategy.
WP11 – Emerging Technologies

In WP 11, five different physical and information technologies were developed to improve and support IPM in a wide variety of cropping systems:

- Airborne sampling and optical sensing methods for macro scale mapping (task 11.1);
- Molecular based diagnostic tools for micro scale identification and monitoring (task 11.2);
- Development of a new generic decision engine for weed control (task 11.3);
- Mating disruption solutions for pest control in protected vegetables and grapevine (task 11.4);
- Precise application of crop protection products based on canopy density sensing (task 11.5).

Task 11.1: First, a new air sampler was developed based on the principle of virtual impaction. This so-called Miniature Virtual Impactor (MVI) (Fig. 11.1) can sample for 24 hours with minimal evaporation, which means spores can be deposited into culture medium to test for viable organisms, or directly into DNA extraction buffer. Burkard and RRES have adapted the device for DNA-based detection of Sclerotinia sclerotiorum using Loop-mediated Isothermal Amplification - LAMP assays. The nucleic acid amplification and the detection of a gene can be accomplished in a single step at a constant temperature (65°C). The method is highly specific and can therefore quickly identify the presence of a target gene. Further work is planned in new projects that will develop DNA-based detection of spores of target species.

Second, novel reflectance images methods to detect disease in fields have been investigated at RRES and DLO. These methods have potential for phenotyping diseases in breeder nursery plots and for directing spray equipment to improve disease control in fields. Wheat experiments were established with several different varieties (with different resistance levels to yellow rust) in which plots with different disease profiles were generated through fungicide spray regimes. These were to obtain spectral canopy reflectance images of wheat plots. Distinctive wavelengths for yellow rust detection in winter wheat were identified: 520 nm was neutral (unaffected by disease), 620-630nm and 650-675 nm were enhanced by yellow rust, 750, 775 and 860nm were reduced by yellow rust. The correct identification of the disease severity was still rather low. Further work is needed to enhance the specificity of the technique and capability to detect early infection stages.

Task 11.2: Two platforms were developed for multi-pathogen quantitative monitoring based on molecular diagnostics tools. Next generation sequencing (NGS) of PCR amplicons and the BioTrove platform were tested in Denmark and the Netherlands. The two platforms complement each other, since the NGS-based platform is generic and will detect and quantify both unknown and known species whereas the BioTrove platform is targeted for selected species.

Air sampling trap has been performed at six locations in the Netherlands, Denmark and the UK. Based on meteorological data and visual assessments of the spore trap tape, a representative series of samples were selected for DNA extraction. Samples have been used for optimisation and development of a protocol for micro scale identification and monitoring. The same samples were used to reveal the total fungal species composition with the two platforms. The use of the platforms can be combined to monitor and identify fungal pathogens in air samples.

Task 11.3: A generic decision support system (DSS) concept was designed and made operational (Fig. 11.2) as an online calculation tool on this URL address: http://130.226.173.145/cp/weeds/parameters.asp?Language=en&ID=PURE

This DSS concept was customised for 3 countries (Slovenia, Italy, Germany), 1 crop (maize), 2 principles for quantification of needs for weed control (reliable/very safe or reliable/risky, previously developed categories that should give the same advise) and 2 levels of expected ‘robustness’ (in terms of weed control), which resulted in a total of 12 DSS prototypes. These 12 prototypes include 70 herbicides, 92 weed species, 4 classes of weed growth stage and 6.769 parameterised herbicide dose-response functions. The DSS also integrates relevant legal restrictions on the use of herbicides, which are also subjected to EU-cross compliance (which may affect EU-subsidies for farmers). Test results indicate that the DSS has the potential to reduce the input of herbicides without jeopardising crop safety with 20-70%. However, more data and work is required to include more crops, weeds, herbicides (and alternative control options) and ‘conditions’ required by professional farmers.

Task 11.4: Two types of mating disruption solutions were developed and tested for their efficacy in vegetables and grapevine crops: a pheromone based disruptor and a vibrational based disruptor.

First, biodegradable dispensers containing the pheromone of the pest moth Tuta absoluta were produced in the Netherlands and tested in tomato crops in Italy. The dispenser was capable of attracting male insects and prevented them from mating with females. Second, a vibrational disruption device for Scaphoideus titanus control was developed (Fig. 11.3). In some insects mate recognition and localisation of the partner are mediated exclusively via substrate-borne vibrational signals. Several experiments were performed to
evaluate and improve the effectiveness of the device for Scaphoideus titanus control in the field and under laboratory conditions. Periods when the device can be turned off without losing any efficacy in controlling the insect mating, and optimal distances between the devices along the wire were determined.

Task 11.5: Canopy adapted spraying in pomefruits trees was developed to reduce the residues on fruits and environmental pollution. A prototype sprayer was constructed, the Canopy Density Sprayer (CDS), and tested in commercial fruit orchards (Fig. 11.4). The sprayer is capable of spraying the proper amount of pesticides based on the canopy density. However, driving speed does not meet up with the commercial requirement and further development will be done after the PURE project.

To reduce significant losses of pesticides to the soil surface during spraying in vegetables, the "VisionSpray" was developed at AU (Fig. 11.5). The VisionSpray is a cell sprayer that consists of two chambers: one for image acquisition and one for spraying. The VisionSpray was tested for its efficacy in WP 4 in radish and cabbage. The efficacy was similar to conventional spraying, but with a reduced input of herbicides.

• WP13 – Co-innovation of IPM
The main result of the co-innovation WP is visible in the co-innovation pilots in Denmark, France, Germany and the Netherlands. Initiated by the pilot teams from PURE, farmers and other stakeholders defined the IPM problem/challenge for their farming systems, identified possible solutions/changes and decided on the most relevant actions for the pilot:
  - In Denmark, the farmers discussed the societal pressure on pesticide use and identified the challenges for their farming system if pesticides are no longer available. This resulted in three on-farm experiments with no input of fungicides and herbicides. In these systems, variety mixtures and/or wide-distance row sowing of winter wheat were used, enabling mechanical weed control and reducing the disease pressure.
  - In France, co-design workshops with farmers resulted the wider understanding that several problems are related to the cropping system itself. Four farmers decided to introduce new crops in their farming system to allow better weed control and improve soil quality. The pilot is continued within the frame of a new project.
  - In The Netherlands, a workshop with farmers on the no-pesticide scenario resulted in the identification of several main challenges (mainly fungal diseases). Next step was an expert session to be informed about the latest research on these issues, a visit to an organic grower and a group discussion on next steps. The pilot will be extended in a new project.
  - In Germany, the pilot organised a workshop with cabbage growers to start up the on-farm experiments of WP4, including an active monitoring of pests and beneficials by farmers. The WP4 experiments were not in all cases successful in the perspective of the farmers, but they learned a lot about monitoring pests and beneficials and will go on with it.

The co-innovation activities in the pilots were facilitated with a trajectory of training and instruction meetings. The training was based on existing concepts and tools and is available for other projects/organisations as well. The training is especially useful for on-going projects.

Secondly, the pilot activities are evaluated in two different ways. The scientific part concentrated on the comparison of the pilots within their institutional context. This resulted in a scientific paper that will be submitted in spring 2015. The lessons and reflections of the participants of the pilots are summarised in a set of small video clips on YouTube (Tab. 13.1) to inspire other farmers and advisors about a more effective connection between scientific/expert knowledge and innovation at farm level.

Potential Impact:
• WP1 – IPM design and assessment methodology
Different stakeholders can benefit from the methodological breakthroughs produced by WP1. Experimenters and advisers involved in diagnoses of commercial fields can use the PURE protocols as a methodological support. The environmental impact of pesticides can now be easily assessed by any adviser, researcher or policy maker at the field or regional level with the SYNOPS-WEB online tool. Farmers and advisers can usefully use the DEXiPM models that were developed to analyse the overall sustainability of potential and actual cropping systems. Innovative models were developed (e.g. PREMISE for the integrated control of apple scab and codling moth on apple orchards) to help efficiently farmers and advisers to implement IPM solutions. The cost-benefit analyses conducted for cropping systems of WP2-7 can be seen as references to be used by farmers, advisers and policy makers. In addition, policy makers can directly use the conclusion of the experimental analysis of consumers’ willingness to pay for IPM products and the review on incentives and policies for the implementation of Integrated Pest Management in Europe. At last, scientists can now use 4 innovative modelling platforms (UNISIM, IPSIM, X-PEST, GMDP toolbox) to develop innovative modelling approaches for IPM. In addition, they can use a wide range of innovative optimisation technics to help design cropping systems less susceptible to biotic stress.
Crop diversity is crucial for minimising pest infestation and reducing pesticide use and crop diversity was an integral part of the IPM systems tested in the WP2 on-station experiments. Due to the duration of PURE no conclusions can be drawn concerning the long-effect of crop rotation on pest population dynamic but as all six experiments will be continued for at least another 3 years this should be possible at a later stage.

Variety mixtures of winter wheat were used in several of the on-station experiments and were also the focus of some of the on-farm experiments. The potential benefits of variety mixtures were illustrated very clearly in the Danish on-station experiment. In all three growing seasons disease level of Septoria in the control plots was lowest with variety mixtures and so was also fungicide use. Weed harrowing was done in the IPM2 system in the two French, the Danish and the German (only the first two years) on-station experiments. The results revealed once again very variable effects of weed harrowing. In the German experiment weed harrowing in winter wheat resulted in unsatisfactory control in the second year of experimentation and was replaced by low herbicide doses in the third year. In contrast in the Danish experiment satisfactory effects were obtained in spring oat. Result and experiences are generally better in spring cereals than in winter cereals and especially spring oat is very suppressive against the proportion of weeds that normally will survive weed harrowing.

Inter-row cultivation was practiced in winter oilseed rape on several locations. Instead of sowing the crop at the standard 12cm row distance it was sown at 50cm row distance allowing for inter-row cultivation. Winter oilseed rape is a very competitive crop and even though weeds in the rows will survive and may produce seeds no yield penalties were observed compared to the systems with broadcast herbicide applications. In recent years significant technical progress has been made with inter-row cultivators, e.g. fitting them with sensor systems permitting the inter-row cultivator to work closer to the crop and at a higher speed. In less competitive crops like sugar beet and field vegetables, weeds in the row are more problematic than in winter oilseed rape. Advanced non chemical weeding tools that can remove weeds in the rows are therefore in high demand.

WP3 – Innovative IPM solutions for maize-based cropping systems

Research conducted by WP3 identified IPM tools that significantly reduce the dependence on pesticides in grain maize production and in most cases are also economically sustainable since their gross margin was not significantly different than the conventional management practiced. Therefore, a practical and locally adapted “toolbox” was provided to farmers, advisors and contractors to be used even in the short term, reducing the environmental impact but also health risks for the farmers. During the project, results of this research have been disseminated to various stakeholders at-by European and International Congresses (i.e. presentations and published proceedings), seminars (i.e. presentations), on PURE web-site (e.g. experimental information, reports), open days to field experiments organized by partners, bulletin and newsletter distribution by partners, publications in technical journals, but also publications in international scientific journals. WP3 already published in European Journal of Agronomy and IOBC Bulletin, and has currently one manuscript under major revision to be published by Pest Management Science journal. WP3 produced a robust dataset that will be further exploited in the coming months by compiling other manuscripts and submitting them to peer-reviewed scientific journals, thus disseminating further the outcomes of WP3 research.

References:

WP4 – IPM solutions for important field vegetable crops

The experiments in WP4 showed that the production of Brassica vegetables is possible to a large extent without using any chemical pesticides. Different guidelines concerning weed, cabbage root fly, and aphid and caterpillar control were composed. They presented tools to show advisors and farmers the way how to reach this goal. Weed control with different mechanical weeding techniques was compared and evaluated. Mechanical weeding performed very good if weather conditions were rather dry. For cabbage root fly control different attempts with alternative plant protection products were described. At the moment the only recommendation to farmers is the drench of transplants with spinosad shortly before transplanting. Other plant protection methods need further investigation and are still too expensive for use in practice.

Aphid and caterpillars were controlled after control thresholds were exceeded. Here, trials showed that biological products (Bacillus thuringiensis and rape oil) were as good as broad spectrum insecticides (lamda-cyhalothrin and dimethoate) and selective insecticides...
The developed guidelines on weed, cabbage root fly and aphid and caterpillar control contain information on the different pests, trials conducted in different countries and show possibilities how the use of chemical plant protection products can be reduced.

• WP5 – Innovative IPM pome fruit systems

WP5 activities were a mixture of testing new IPM tools and at the same time integrating those into existing whole IPM strategies. The impact of the new IPM tools would take a few more years of research to reach fully the implementation into practice. On the other hand, some of these new tools were greatly welcomed by the commercial fruit growers who participated in testing them in their orchards. Focus was on four pathosystems in orchards. These were apple scab and codling moth in apple and brown spot and pear psylla on pear. The potential impact, the main dissemination and exploitation of results is mentioned hereafter per pathosystem.

Substantial progress was made in bio-product development based on the biological control agent (BCA) Cladosporium cladosporioides H39 for apple scab control by WP 9 “Plant-pest-enemies interactions”. Different formulations of this product from WP 9, task 2, were tested on field efficacy in commercial organic orchards in our WP5. It is believed that this will provide a commercial BCA product usable in both organic and IPM orchards. During the on-farm experiments, growers visits were arranged and by that disseminating the results. Based on the enthusiasm of the fruit growers it is expected that sanitation practice will be more commonly used.

For codling moth control, the on-farm experiments with enclosure nettings were conducted in the “Alt’Carpo” network commercial apple orchards under either organic or IPM management. It was demonstrated that nettings are commercial viable if there is also a hail damage risk. Advisors organised growers meetings to disseminate also the side effects of nettings. It is expected that results will be implemented quickly in practice in regions with substantial risk on hail damage.

For brown spot of pear it is expected that Sordaria containing products will be commercially developed base on the PURE results. Moreover, the on-farm experiments on the combination of sanitation and decision support encountered enthusiasm within growers during dissemination activities. So, it is expected that a lower amount of fungicide sprays will be used against this disease in future. The dissemination meetings with growers and advisors to discuss sustainable pear psylla control were so successful that during the on-farm experiments, farmer gradually shifted towards the more sustainable IPM strategy, by omitting harmful pesticides. It is expected that this IPM strategy will be further implemented quickly all over the Netherlands.

Note that intense interaction between WP 11 “Emerging technologies” and WP 5 “Innovative IPM in pome fruit systems” took place for precise sensing and canopy adapted spraying methods. Both on-farm testing and stakeholder interaction resulted in interest from a commercial company to participate in further development.

• WP6 – IPM solutions to reduce pesticides reliance in grapevine

The trials carried out in WP6 identified different levels of importance of the pest and disease in EU according the environmental conditions and the grapevine varieties used in the different regions/countries. Another source of variation is the type/size of farm and its organisation. Therefore there are areas where certain IPM tools can be easily applied (i.e. mating disruption against Lobesia botrana where there are sufficiently large farms or cooperative organisation among farmers that can cover a wide and sufficient area for mating disruption to be efficient) and areas where they cannot (i.e. in central EU the reduction of inoculum of Powdery mildew by Ampelomyces quisqualis is not possible because the resting bodies of the pathogen are formed throughout the season). Therefore after an accurate ex-ante analysis specific IPM solutions have been chosen in the different regions under study. In each region the solutions were targeted to the most relevant pest/pathogens which are requiring the highest pesticide input. The IPM solutions tested in general significantly reduce the dependence on pesticides in grape production and in most cases are also economically sustainable since their gross margin was not significantly different from the conventional management practiced. As a consequence, a practical and locally adapted “toolbox” was provided to farmers and checked in term of sustainability. IPM toolboxes were composed by biological alternative to pesticides, DSS to reduce or optimise the use of chemical sprays, agronomic practices and combination with resistant varieties. Solutions coming from WP9 and WP11 have been tested under commercial-like conditions with the aim of evaluating economic and technical feasibility. During the project, results of this research have been disseminated to various stakeholders by European and International Congresses (i.e. presentations and published proceedings), seminars (i.e. presentations), on PURE website (e.g. experimental information, reports), during open days to field experiments organised by partners, with bulletin and newsletter distribution by partners, publications in technical journals, but also publications in international scientific journals.

• WP7 – IPM solutions for protected vegetables

Within this workpackage, much attention has been paid to scientific writing, and to conference calls. In Spain, field days and training courses have been organised in a demonstration greenhouse allowing, students, technicians and growers to learn about pests and beneficials recognition and sampling methods. Moreover than 25 on-farm experiments have been carried out in collaboration with cooperatives and farmers to implement the latest IPM solutions. In most cases, these achievements resulted in an increase of the grower benefits and the growers and cooperatives have
adopted the tested biocontrol strategy.

More generally, the IPM solutions displayed have been country- and context-dependent. Currently, IPM in protected tomato production seems mature enough to be recommended and applied in European Southern countries with an important reduction of chemical treatments. Main airborne pests (even new invasive ones like T. absoluta) can be controlled with releasing biological control agents. General predators are now used against main airborne pests like T. absoluta and whiteflies. Whenever needed other specialist predators and parasitoids can help and reinforced the generalist predators’ control of pests. Also other minor pests can be controlled biologically, as it is the case of spider (Tetranychus urticae) and predatory mites.

The common trait in all cases has been more production, more quality and marketable production and finally the access to export markets that pay extra prices for this IPM quality production as we have demonstrated in the cost benefit analysis. In conclusion, IPM in protected tomato production in Southern Europe can be resumed in a much better overall sustainability performance from all points of view: economic, social and environmental. All of this constitutes a real lever to encourage growers to shift towards IPM strategy.

- **WP8 – Pest evolution and enhancement of the durability of IPM solutions**

WP8 objectives were to provide tools and concepts for using diversification of IPM to counteract the emergence of super strains of diseases, weeds and pests, and mitigate the negative consequences thereof.

Modelling studies in WP8 on evolutionary processes in pathogen and weed populations elucidate principles that can guide practical strategies for disease and weed management. This work is strategic and is intended for impact in the longer term, through guiding the development of gene deployment strategies for plant resistance that prolong the effective life of genes, and to guide weed management strategies that take advantage of the fitness costs of herbicide resistance to remove such biotypes gradually from the weed flora. Modelling is the only way in which such long term strategies can be evaluated and designed ex-ante. Measurements on the other hand give immediate clues on practical actions. For instance, the information gathered in yellow rust biotypes is included immediately in practical advice to farmers on the control of yellow rust in wheat.

Literature research on the durability of biological control against plant pathogens and pests likewise gives important clues for risks and opportunities in the management of biocontrol to avoid resistance. Work on the development of insect viruses for biocontrol of Cydia pomonella and Cydia molesta resulted in immediately applicable strains that may be proposed in the future to practical apple growers (patent pending). All in all, the WP8 package has yielded important insights and practical methods or products that will benefit IPM in the near future (particularly the use of insect viruses) or the long future (strategy development for avoiding super strains and managing these following emergences).

- **WP9 – Plant-pest-enemies interactions**

Task 9.1: the main outcome is better information about how to use priming agents for disease protection in tomato. Effective plant activators emerging from these trials were β-aminobutyric acid (BABA) and fructose. There are opportunities for tomato breeding programmes to select for genetic traits that increase the resistance response to specific combinations of chemical defence activators, whilst minimising the costs in terms of plant growth reduction.

Task 9.2: formulations to improve the longevity of fungal biocontrol agents and more efficacious strains have been developed. These included an improved strain of Trichoderma atroviride (SC1) with conifer bark formulations that improve its longevity and efficacy for controlling soil borne diseases and strain ITA3 of Ampelomyces quisqualis in a novel formulation that enhanced germination and hence control of powdery mildew diseases.

Task 9.3: improved quality control and performance of biocontrol agents was achieved by implementing morphological and molecular characterisation protocols was developed. For better performance, at least one generation of the parasitoid should be completed on the same host before its release. Furthermore, BCA performance and efficacy against the target pest is maximised when rearing temperatures are the similar to those experienced in the field into which they are delivered.

Task 9.4: a number of promising natural products were characterised including Ajuga chamaepitys extract, DiCQs and diCT with activity against insect pests; caffeic, chlorogenic and ferulic acid with activity against mycotoxin biosynthesis, and benzoaxazinoids with activity against Fusarium head blight.

- **WP10 – Ecological engineering for IPM: from field to landscape**

Manipulating ecological processes to achieve reliable and predictable pest suppression has proven difficult, and there are few examples of the effective use of ecological engineering strategies as part of an IPM tool box. The examination of several ecological engineering approaches in PURE yielded complex and sometimes ambiguous results, even where effects were positive with respect to the suppression of pests. This should be accepted as the default position for ecological engineering studies and is an important message to communicate to all stakeholders. This message will be presented, in addition to the general principles and potential benefits of ecological engineering, to policy and industry audiences through events such as LEAF Open Days in the UK. PURE has also produced a set of findings that will positively impact on the development of ecological engineering strategies. Key, general findings to
be emphasised include the importance of tailoring suppressive soil management to the pathogens present, the need to focus on the
delivery of pest control services within the open field to achieve effective conservation biocontrol, and that specific, manageable
features rather than complexity per se, can be responsible for landscape scale effects on pest and natural enemy populations. In
addition, a number of system specific results offer promising opportunities for development, for example the optimisation of crop
rotation for the area-wide control of Diabrotica and the landscape scale management of codling moth. These and other results will be
actively promoted and disseminated through the publication of papers and conference presentations. This will also include
communication of technical developments such as the disease assays for soil borne pathogens, and the AgBioscape modelling system
which we believe will have value in modelling a wide range of systems and as the potential basis for decision support systems. PURE
partners are also taking forward the insights gained to be incorporated into future EU and national research programmes, and to be
disseminated to future generations of agricultural scientists through their teaching programmes.

- **WP11 – Emerging Technologies**

WP 11 aimed at developing new technologies for crop protection based on the combination of detection and monitoring methods at the
macro scale (i.e. on whole field scale) and micro scale level (i.e. certain positions in the field) with decision engines and innovative crop
protection solutions. This resulted in the development of a validated decision support engine which is available online

Farmers and advisors in three countries (Italy, Slovenia and Germany) used the DSS and were able to reduce their herbicide use in
maize with 20 to 70%. The DSS engine is generic and will be extended to other countries and non-perennial crops, potentially reducing
herbicide use in a wide range of crops and countries. Secondly, a prototype mating disruption device based on vibrations for use in
grapevine was developed and tested. The prototype will be optimized in cooperation with OPTOELETTRONICA ITALIA S.r.l.
and prepared for commercial exploitation. Third, a new air sampler was developed based on the principle of virtual impaction: the MVI.
This automated air sampling device for collection of fungal pathogen spores, pollen grains and other biological particles has been
patented (Patent GB2496995) and further development by Burkard Ltd and RRES is in progress. Fourth, the Canopy Density Sprayer
(CDS) has been demonstrated on several occasions to pomefruit growers in the Netherlands. Commercial exploitation of the CDS will
be possible after improvement of the driving speed. Fifth, a cellsprayer (VisionSpray) has been developed for vegetable spraying and
was capable to control weeds in radish and cabbage with reduced herbicide input of 43-69%. The VisionSpray is ready for validation in
other crop-herbicide combinations.

- **WP13 – Co-innovation of IPM**

The results of WP13 are especially relevant in the context of Horizon 2020 (Multi actor approaches) and European innovation
partnerships. These results show that an effective connection between research and innovation is possible, but not easy to organise
within a scientific environment (like FP7). The structure of WP13 could be a nice example for organisations and research / innovation
projects to introduce a co-innovative approach: the room for experimentation (and failure) and the combination of training/reflection,
learning on the job in pilots and a structured monitoring and evaluation proved to be successful and could be translated to other cases
as well.

- **WP12 – Knowledge interaction, dissemination, training and technology transfer**

  **Task 12.1 Dissemination through publications and at scientific and technological Events**

Dissemination of PURE knowledge and results among the technical and scientific community was realised through joint articles in peer-
reviewed scientific journals and technical journals and notes in national and regional agricultural magazines.

PURE also made available most of the deliverables and reports produced; 89 reports were uploaded on the website. The table 12.1
gives the total number of publications available on the website.

PURE participated to the international conferences organised by AFPP (French organisation) in Lille, first in 2011, to present the project
with a poster and secondly in 2015, to present key messages about the lessons and results from Pure.

  **Task 12.2: Website, brochure, newsletters and booklets**

The PURE website was developed by ACTA. The website was the main tool to disseminate information and documents from the PURE
community (www.pure-ipm.eu ).

The Figure 12.1 shows details available on the homepage:

- Access to Project information, WPs, publications, information on countries and partners, links to other European projects;
- Latest News and events.
This website was created on June 2011 and regular information, news and reports were posted in order to maintain the number of visits per month around 2500 to 3000 visits (Fig. 12.2).

The main pages consulted by web visitors are distributed according to different categories as shown on Figure 12.3. General information (WPs, partners) has been accessed up to 30% and the technical information (publications, congresses, others) up to 40%. The last part concerns news (events = agenda, news) from the project (Fig. 12.3). A start-up brochure was published to present the aims of PURE. It was published on electronic support ready to be printed to be distributed by partners during events. This brochure was available on the website in July 2011.

Three series of booklets were produced and made available on the project website to create a continuous flow of information from the project to the public. A complete booklet gathered all information and a special document were produced for each workpackage from the complete booklet. The main topics of the booklets were:
• 2013 = cropping systems activities with a presentation of the approach (IPM design and assessment methodology), the first results and the next steps.
• 2014 = new knowledge and technologies for IPM with a presentation of the approach, the first results, the interaction with cropping systems activities and the next steps.
• 2015 = Results and lessons from PURE with a description of the approach, the studied pests, the complete technical results, the sustainability of IPM solutions, the innovative methods and the limits and conditions of success and adaptations needed.

Newsletters were produced annually (with an annual summary of the project) and periodically (news and events in brief about the project on the website homepage). Each newsletter was made available on the website and sent by email via a mailing list. This mailing list, common within the ENDURE network, has grown during the project. The first annual newsletter was sent in August 2012. The second one was sent in August 2013. The third one was sent in March 2014. The fourth and last one was sent in April 2015.

Task 12.3: Farm days and virtual field visits
Farm days were one of the main tools used for the direct dissemination of project outputs among farmer communities in each country. These farm days allowed direct knowledge transfer to farmers and extension services of innovative IPM solutions designed by Pillar 1 and also innovative tactics designed by Pillar 2 to be included in IPM solutions.

Dissemination also places extra effort on innovative learning methods and the active involvement of different stakeholders groups. The latter approach includes farm days and virtual field visits conducted in a participatory approach for farmers and advisors. In total, 16 virtual field visits in each farming system, under the coordination of WP2-7 leaders, were made available on the website (Fig. 12.4).

Each virtual visit includes pictures with legends and a complete file describing the field tests. These virtual visits are in English and in local language. Using English gives to stakeholders from a country the possibility to visit experimental fields from another country, and using the local language facilitates accessibility to information for local stakeholders who do not understand English.

Task 12.4: e-based learning materials
The e-learning material is dedicated to trainers and was produced during the project based on main results of all the WPs. The objective is to provide a ready-to-use material / presentation supports. This material gives the possibility to have more information via tool tips and links to complete information available on the PURE website (deliverables, booklets, scientific publications, etc.).

At the end of the project, one e-learning material for each cropping systems activity using the “Results and lessons from the PURE booklets was provided. It is an interactive slideshows of the booklets produced in each pillar 1 workpackage, which gives to advisers and trainers an overview of the main results from PURE. Links from the slideshow to virtual visits, reports and deliverables allows the reader to get the complete information about results. Some workpackages provided additional e-learning material to show some technics or methods.
Task 12.5: Support to policy implementation
In WP12 a task was specifically dedicated to the support to policy implementation. The aim of this task was to facilitate interactions with Member State and European stakeholders directly or indirectly involved in the policy-making process. The objective of these interactions was to take findings from the PURE experimentations and decision process in terms of IPM implementation opportunities and bottlenecks to the policy sphere.

Members of PURE are actively involved in the European Member State Expert Group on the implementation of the Directive 2009/128/EC. The involvement also implies discussion on how to achieve and ensure IPM implementation on European scale. A discussion forum on the option and opportunities as well as the bottlenecks took place in May 2014 with representatives from EU MS and COM (DG SANCO). Experiences and lessons learnt from the PURE project were discussed. In return, policy stakeholders shared their points of view regarding the desirability and feasibility of the IPM solutions proposed by PURE.

Additionally close interaction and networking exists between the former Network of Excellence ENDURE (now ERG ENDURE) and the newly initiated ERA net C-IPM (Collaborative IPM). Those networking activities enable the PURE network to feed the newest research findings as well as the remaining challenges into the current and future research programming.

Task 12.6: PURE stakeholder congresses
PURE congresses targeting stakeholders were organised in years 2 and 4 of the project, respectively in Italy (Riva del Garda – March 2013) and Poland (Poznan - January 2015). The purpose of these congresses was to provide a forum for: (a) the dissemination and discussion of results from the PURE project, (b) the presentation and discussion of results from other IPM projects, so that PURE activities can be presented and reviewed in the context of other R&D programmes, (c) workshops on the topics addressed by Pillar 1 and 2 working groups.

The programme of each congress was prepared by the PURE Executive Committee and the local congress organising committee. The proceedings from each PURE congress were published on a specific website, in order to make use of existing editing facilities and substantially reduce publishing costs.

- FUTURE IPM IN EUROPE- Riva del Garda (Italy) March 19-21 2013
  The congress attracted more than 500 participants (i.e. academia and stakeholders) from Europe and all over the world (37 countries). The main participants were coming from Italy, France and Germany (Fig. 12.5).

- IPM innovation in Europe - Poznan (Poland), January 14-16 2015
  The congress, a three-days event, attracted more than 190 participants (i.e. scientists and stakeholders) from Europe and all over the world (23 countries) (Fig. 12.6).

In total, during the two congresses, 240 posters were presented, and about 190 oral presentations were done over the six days, showing that our PURE events were a great success.

List of Websites:
The address of PURE public website is http://www.pure-ipm.eu/

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