Evaluation of potato-based farming systems in Croatia, regarding their sustainability

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EVALUATION OF POTATO-BASED FARMING SYSTEMS IN CROATIA, REGARDING THEIR SUSTAINABILITY

MASTER THESIS

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STUDENT STATEMENT
ON THE ACADEMIC INTEGRITY

I, **Marie Machačová**, JMBAG 601983 11 0178138104 6, born on 25th August 1998 in Brandýs nad Labem – Stará Boleslav, Czech Republic, declare that I independently prepared the Master thesis entitled:

EVALUATION OF POTATO-BASED FARMING SYSTEMS IN CROATIA, REGARDING THEIR SUSTAINABILITY

With my signature I guarantee:

- that I am the sole author of this Master thesis;
- that all literature sources used, both published and unpublished, are appropriately cited or paraphrased and listed in the reference list at the end of the Master thesis;
- that this Master thesis does not contain any parts of work previously submitted to the Faculty of Agriculture or other higher education institutions for the purpose of completing university or specialist study programme
- that the electronic version of this Master thesis is identical to the printed version which has been reviewed by the Committee and approved by the mentor
- that I am acquainted with the regulations of the Code of Ethics of the University of Zagreb (Article 19).

In Zagreb, on ________________ ________________________

Signature of the student

UNIVERSITY OF ZAGREB
FACULTY OF AGRICULTURE

REPORT
ON EVALUATION AND DEFENSE OF GRADUATE THESIS

Master thesis of the student **Marie Machačová**, JMBAG 601983 11 0178138104 6, entitled

EVALUATION OF POTATO-BASED FARMING SYSTEMS IN CROATIA, REGARDING THEIR SUSTAINABILITY

was defended and evaluated with the grade _____________________, on ________________.

Committee: signatures:

1. Prof. Renata Bažok, PhD mentor ____________________________
2. Prof. József Kiss, PhD co-mentor ____________________________
3. Assoc. prof. Darija Lemić, PhD member ____________________________
4. Prof. Milan Poljak, PhD member ____________________________

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Content

Summary

Of the Master thesis of student **Marie Machačová**, entitled

EVALUATION OF POTATO-BASED FARMING SYSTEMS IN CROATIA, REGARDING THEIR SUSTAINABILITY

Croatian potato production is threatened by numerous pathogens and arthropod pests, for e.g. late blight (*Phytophtora infestans* deBary), early blight (*Alternaria solani* Sorauer), Colorado potato beetle (*Leptinotarsa decemlineata* Say.), wireworms (*Agriotes* spp). Chemical pesticides are sprayed regularly to suppress pests and avoid yield and quality losses. The aim of the thesis was to understand the current situation in potato production in Croatia in the Međimurje county and to evaluate the sustainability of the production. A questionnaire, focused on IPM implementation and broader plant protection, was created. Important data were obtained, analysed and shown in graphs using the excel. Obtained data showed, that current potato production in Croatia is dependent on chemical pesticide. However, farmers are opened to biological and other alternative control solutions, if they could access more information about it and if they had a chance to discuss appropriate approaches with an experienced advisor/mentor.

Keywords: biological pest control, integrated pest management, potato production, sustainability

Sažetak

Diplomskog rada studenta/ice **Marie Machačová**, naslova

EVALUACIJA SUSTAVA UZGOJA KRUMPIRA U HRVATSKOJ S OBZIROM NA NJIHOVU ODRŽIVOST

Proizvodnji krumpira Hrvatskoj prijete brojni uzročnici bolesti i štetnici člankonošci, npr. plamenjača (*Phytophtora infestans* deBary), koncentrična pjegavost krumpira (*Alternaria solani* Sorauer), krumpirova zlatica (*Leptinotarsa decemlineata* Say.), žičnjaci (*Agriotes* spp.). Da bi se spriječio napad i izbjegli gubici prinosa i očuvala kvaliteta, redovito se primjenjuju kemijski (sintetski) pesticidi. Cilj diplomskog rada bio je razumjeti trenutno stanje u proizvodnji krumpira u Hrvatskoj na području Međimurske županije i ocijeniti njenu održivost. Izrađen je upitnik usmjeren na provedbu mjera integrirane zaštite bilja te na širi kontekst zaštite od štetnih organizama. Prikupljeni podaci su sistematizirani, analizirani i grafički prikazani u MS Office programu Excel. Dobiveni podaci pokazali su da trenutna proizvodnja krumpira u Hrvatskoj ovisi o kemijskim pesticidima. Poljoprivrednici su otvoreni za primjenu alternativnih rješenja i proizvoda za biološko suzbijanja no smatraju da im nedostaje više informacija i rasprava i razgovor o odgovarajućim pristupima s iskusnim savjetnikom/mentorom.

Ključne riječi: biološko suzbijanje štetnika, integrirana zaštita bilja, održivost, proizvodnja krumpira

1. Introduction

European potato farmers are currently facing multiple challenges. The long-term sustainability of the production is threatened by loss of yields and increased disease and invertebrate pest outbreaks, that are caused by one of the major challenges – change in climate which leads to changed weather patterns (Anonym, 2023). Another upcoming challenge in crop production is European Green Deal (European Commission, 2019), established by EU phytosanitary and environmental policies. The EU Green Deal policies have introduced **Farm to Fork Strategy** (European Commission, 2020) and **Biodiversity Strategy 2030** (European Commission, 2020a), which defined the common challenge of reducing dependence on synthetic chemicals, improving food quality and increasing the potential for the development of more bio-based and biotech-oriented production systems.

Potato production in Croatia is threatened by various pathogens (late blight (*Phytophtora infestans* deBary) and early blight (*Alternaria solani* Sorauer)), and invertebrate pests (Colorado potato beetle (*Leptinotarsa decemlineata* Say.), wireworms (*Agriotes* spp.) and various species from the Noctuidae family)). Potato crops are regularly treated by chemical fungicides and insecticides to save yields and prevent damages. Based on that, it has been assumed, that there is limited knowledge about alternative and more sustainable methods, that can help with invertebrate pest and disease control in potato-based cropping systems.

Integrated Pest Management (IPM) is a strategic approach to crop protection and part of a broader concept of integrated production aimed at the overall sustainability of agricultural production on farms. Farmers in the EU must comply with the eight general principles of IPM (European Commission, 2024). To meet this challenge, farmers must have knowledge, skills and competence in biological and biotechnical control agents and in the implementation of various crop protection strategies that can reduce risks to the environment and humans. Potato cultivation is of high importance in Croatian agriculture and contributes to food security, economic development and income generation in rural areas.

Changes in farming practices, such as the adoption of different cropping systems, can affect not only agricultural, but also economic and environmental performance and overall sustainability of farms. Such changes may require investment and training to implement. Farmers' perceptions of the relative performance of new or innovative practices can influence the system changes adaption. Among these factors belong for e.g. farmers' innovation adoption/risk aversion preferences, socio-demographic characteristics of farmers and farms (age, farm size, education level, farm structure, off-farm employment, location, etc.), and in particular the information sources and methods used to access information (Jameson et al., 2024).

1.1. Aim

The aim of this research is to map the current situation on sustainability in potato production and plant protection measures applied against the main pests by potato growers in Croatia. The evaluation aims to understand the ecological impact, production efficiency, and economic reliability of currently used farming practices to develop strategies for more sustainable agriculture in Croatia.

2. Literature review

2.1. Sustainability in agriculture

Chemical pesticide use made it possible to save the yields, that are endangered by arthropod pests, diseases and weeds, drop more complex crop protection approaches, and simplify cropping systems in fields. However, nowadays the intensified farming approaches seem to have reached their limits, and questions regarding their sustainability are being raised more and more often. The unjustified use of chemicals in agriculture relates to water, soil, and atmosphere contamination, biodiversity loss, and unintended health impacts on the human population. Intensive chemicals-based pest management in crop production is currently endangered by the development of pest resistance and decreasing availability of active substances. Consequently, farmers are in need of cropping systems that would be less dependent on chemical pesticides. Therefore, the European Union legally prescribed the implementation of Integrated Pest Management which fits into sustainable farm management (Barzman et al., 2015; Deguine et al., 2021). Changes towards sustainable management within farming, including adoption of different various cropping systems, may affect not only the crop itself but also environmental and economic performance just as the overall sustainability. These changes may need training and investments to be accomplished (Jameson et al., 2024).

2.2. Integrated pest management

The system of Integrated pest management (IPM) is an approach, in which all available plant protection methods are carefully considered and appropriate measures are chosen to suppress the development of pests (organisms known to be dangerous to desired crop) when at the same time minimizing risks to the environment and human health by keeping the use of any interventions such as plant protection products to levels which are ecologically and economically justified. IPM focuses on growing healthy crops with as little impact as possible on agroecosystems and promoting natural pest control mechanisms (Sustainable Pesticide Use Directive 2009/128/EC, Barzman et al., 2015).

According to Barzman et al. (2015), the system of IPM consists of eight principles (P): P1 – prevention and suppression, P2 – monitoring, P3 – decisions based on monitoring and thresholds, P4 – non-chemical methods, P5 – pesticide selection, P6 – reduced pesticide use, P7 – anti-resistant strategies, and P8 – evaluation as it is presented in figure 2.1.

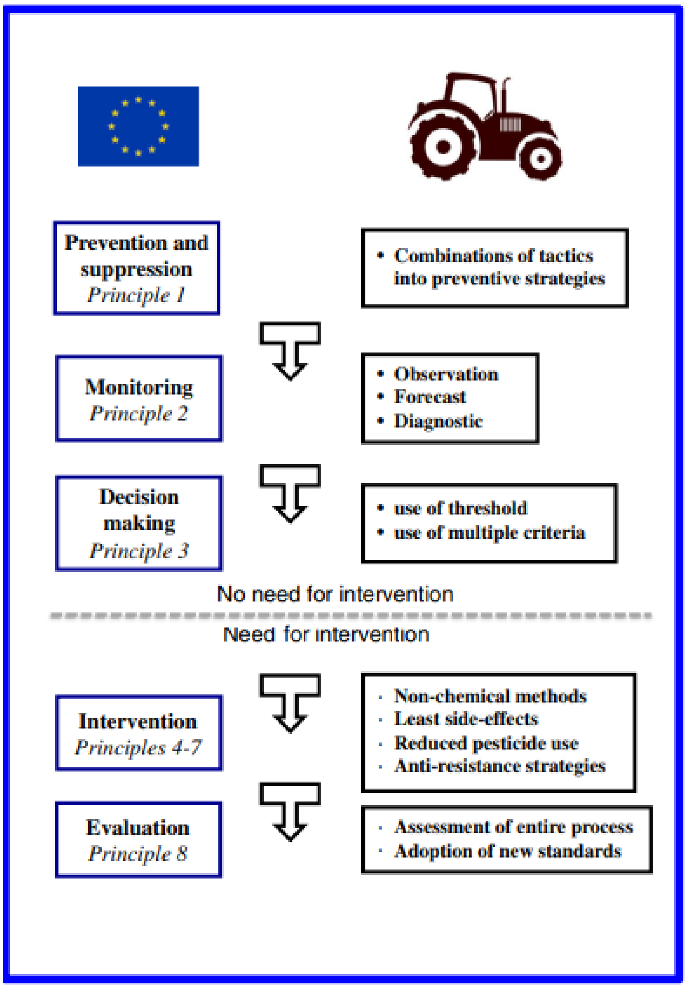

Figure 2.1. The sequential rationale behind the eight principles of IPM (P1- P8). (Barzman et al., 2015)

Principle 1 – Prevention and suppression

According to Barzman et al. (2015), the first and most important rule of every agricultural production system should be "Prevention is better than cure" as with an efficient prevention approach, it is possible to avoid a need for a cure later in the season.

Prevention: creating such an environment in the cropping system, in which major yield and/or economic losses caused by harmful pests are less likely to occur.

Suppression: reduction of occurred pests or a reduction of caused harm. Suppression complements prevention.

By this principle, we understand, that the aim is not to entirely eliminate pests (like with chemical control), but to avoid any pest's population to cause damages in the cropping system or becoming dominant. With the new technology detection methods, some aspects of prevention, such as detecting pathogens in soil and substrate, and weed-seed free planting materials, can now be examined better. Numerous pathogens are associated with seed contamination, and they can become potential sources of diseases in the following year.

The weed seed contaminating harvest can also cause serious problems during the following season. New sorting technologies and certification of disease-free seeds, bulbs, seed potatoes, and cuttings can effectively avoid problems if measures are taken on time – before the seed certification of harvested seeds. Manure and soil substrates can be examined with modern molecular multiplex screening technologies for qualitative and quantitative disease situation assessment. These modern diagnostic methods assure better decision-making when choosing the following crops and their cultivars. A web-based system that detects particular nematode pathotypes has been developed as a handy tool for potato farmers to adjust rotation strategies in the fields. For even better improvement of prediction methods, agriculture needs new technological tools with higher sensitivity to detect pathogens in latently infected plants and seeds.

An important part of prevention development is plant breeding of resistant cultivars. Despite fully resistant cultivars are not likely to be discovered, even partially pest-resistant and disease-tolerant crop cultivars can lower dependence on chemical pesticide use in fields. Cropping of such bred cultivars will require continuous monitoring and a combination of additional measures (Barzman et al., 2015).

Combinations of tactics and multi-pest approach

More effective and sustainable results can be achieved by combining control tactics into crop management systems rather than just single-tactics methods. Examples of various methods that can be combined:

- exploiting plant genetic resistance against multiple pests
- diversifying cropping systems in time and space
- integrating pest management practices and landscape effects within pest management

According to Barzman et al. (2015), **FP7 PURE project** evaluated the suitability of strategy combinations on six different cropping system types. The program has successfully tested following practices in different combinations in maize-based cropping systems:

- pre-emergence herbicides
- establishing a false seed bed
- harrowing at the 2–3 leaf stage
- use of low-dose post emergence herbicide
- hoeing combined with postemergence band-spraying
- *Trichogramma* releases against European corn borer (*Ostrinia nubilalis* (Hübner))

In cases, that make it possible, control strategies testing considers multiple pests, as control of one pest could affect another. The project Hortlink SCEPTRE based in the UK provides a multi-crop, multi-season, multi-pest 4-year-long testing. It takes place in an on-farm conditions and it combines various options of control against raspberry beetle, *Botrytis,* aphids, precision monitoring, and biopesticides in protected raspberry systems. The most favourable combination led to reduced pesticide need by 30% and the pest suppression had as good results as current chemical pesticide control in each region. For further development of suitable multi-pest non-chemical approach combinations, further on-farm research is required to consider the workability of suggested approaches from the farmer's point of view (Barzman et al., 2015).

Crop rotation

By rotation of crops, which provides temporal and spatial diversity, we can effectively prevent and minimize pest pressure, especially in organic arable production, where it is the best-known alternative to synthetic pesticide use (Barzman et al., 2015).

In a study by Vasileiadis et al. (2013) two rotation systems of maize have been compared. It has been shown that maize that has been cropped applying only simple rotation with winter wheat (*Triticum aestivum* L.), was dealing with greater pest pressure than maize cropped in more diverse rotation systems, which included alfalfa (*Medicago sativa* L.), sunflower (*Helianthus annuus* L.), winter oilseed rape (*Brassica napus* L.), soybean (*Glycine max* (L.) Merr.) and grass. In the more diverse crop rotation system, the life cycles of maize pests have been interrupted and therefore the next time maize was cropped, the pest pressure was lower. According to Meissle et al. (2009), rotating maize with more crops can also reduce expansion of weeds.

Crop management and ecology

Numerous crop management practices, that do not seem to be related with pest control, can lead to reduced (or increased) pest and disease pressure. Practices that influence plants vulnerability are for e.g. fertilization (can affect sap-sucking insects, mites and plant pathogenic fungi), mechanical weeding (can unintentionally damage crop plant tissue and create a gateway for pathogens), crop residue management (can affect the pests' capacity to overwinter) and tillage system (often influences wealth and structure of soil-borne diseases and amount of weeds) (Barzman et al., 2015).

In maize production, applying fertilizer in subsurface or surface bands instead of broad application can enhance competition of the main crop against the weeds. Likewise, higher plant density or narrower row space can enhance competition of maize in water and nutrient absorption against weeds. Other measures that help supress weeding are cover cropping, delayed irrigation and maintenance machinery clean of weed seeds/plants parts to avoid distribution in between fields (Meissle et al., 2009).

<u>Principle 2 – Monitoring</u>

An essential aspect of IPM programmes is the assessment of the risk of the crop suffering economically significant levels of damage (Ortega-Ramos et al., 2021). If available, pests and diseases must be monitored by sufficient tools and methods. This should include not only observations in the field but also scientifically based early diagnostic and forecasting systems (European Commission, 2024).

According to Ortega-Ramos et al. (2021), monitoring can be beneficial in of cabbage stem flea beetle (*Psylliodes chrysocephala* Linnaeus) (CSFB) control in oilseed rape (OSR) cropping systems. This pest is harmful in its larval and adult stage, therefore both life stages are being monitored. Monitoring of the adult CSFB is done mostly in autumn to observe migration into newly sown OSR crops and yellow water traps are used for this purpose. Yellow water traps are placed at the ground level in the newly sown field and CSFB caught in the trap are counted weekly. Despite the increased manual labour (water transportation, identifying and counting of CSFB etc.), the water traps have higher efficacy in comparison to yellow sticky traps (that are not always sticky enough). Currently, an image-based automatic identification applications (to simplify and speed up the assessment), that automatically classifies and counts insects, are becoming available on the market.

Ortega-Ramos et al., (2021) further states, that the most effective CSFB larvae monitoring is dissecting of OSR plants using a scalpel and counting the larvae found within the stem and leaf petioles. However, this technique is quite time-consuming and technologically demanding (binocular microscope is needed). As a less complicated method is considered the larval evacuation method, that is based on drying field-collected plants in a container for 1 – 3 weeks and calculating larvae which have left the plant. This method is however way less efficient as a) not all the larvae exit the plant and b) the delay between collection of samples and obtaining results is too long and therefore it is not possible to take accurate measures on time.

Principle 3 – Decision based on monitoring and thresholds

Based on the results of the previous principle – monitoring, farmers or other professional users need to decide if and when they will apply any plant protection measures. Scientifically based threshold values must be used while decision making. Typically, if thresholds are given, they consider each pest, region, area, climatic conditions and the specific crop (European Commission, 2024). Economic thresholds are the lowest pest population densities (pest per plant / part of plant / unit area) at which pest control measures should be applied to prevent economic losses (Ortega-Ramos et al., 2021).

Yeh et al. (2023) observed that there are economic advantages of monitoring-based decisions in *Drosophila suzukii* Matsumura treatment in blueberry production in Oregon. The standard procedure without monitoring is to spray-treat *D. suzukii* with chemical pesticide every 3 days. In this experiment, one of the strategies was to lower the pesticide application to 1 time a week (S1) without doing any monitoring. With monitoring techniques (adult trapping S2; fruit sampling S3 and S4) more precise spraying timing has been applied. It has been shown in this study, that that the original conventional strategy, which includes spraying every 3 days, is not the most profitable strategy due to high pesticide cost, but the least profitable strategy turned out to be the S1 (in which the spraying has been lowered to 1 application per week without previous monitoring). Best results (best harvest x amount of pesticide used) have been achieved when the frequency of pesticide spraying was monitor-based, even though the overall number of sprayings was similar to S1).

Principle 4 – Non-chemical methods

Physical, biological and other sustainable non-chemical approaches must be chosen over chemical options, if they can provide satisfactory results (European Commission, 2024).

In the Californian strawberry production, is the lygus bug (*Lygus hesperus* Knight) the most significant pest, that is hard to suppress even with chemical pesticides. Experiments to treat it non-chemically have been done with azaridachtin, that is a botanical equivalent to chemical insect growth regulators and entomopathogenic fungi, that affects all insect's life stages. In laboratory studies, an improved efficacy has been proven when combination of low rates chemical pesticides and *Beauveria bassiana* (Balsamo) Vuillemin was used. Even though field studies results were not 100% consistent, it has been shown that control by *B. bassiana* alone is not efficient enough, but in combination with azaridachtin and *Metarhizium brunneum* (Petch), much better efficacy has been shown. Based on this results it has been stated that rotation of chemical pesticide use with non-chemical options as are *B. bassiana*, *M. brunneum* and azaridachtin can be one of important options to treat *L. hesperus.* This kind of rotation treatment could lower the chemical pesticide use (Principle 6) and slow down the resistance development (Principle 7) (Dara, 2016).

Principle 5 – Pesticide selection

Selected pesticides must be as specific as possible for the targeted pest and should have as little side effects on human as possible (European Commission, 2024).

Numerous cases of chemical pesticides causing harm to non-target beneficial organisms and natural enemies are documented. In the early 1970s, an immoderate use of non-selective chemical pesticides in Swiss vineyards and orchards almost eliminated populations of predatory mites and led to acaricide resistance in spider mites. Consequently, spider mite outbreaks became uncontrollable by chemical means and had to be regulated with newly designed programmes, that aimed to preserve reintroduced populations of previously naturally occurring predatory mites (Barzman et al., 2015).

IPM systems can only be successful, if there will be alternatives to plant protection measures and conventional pesticides, that can manage crop pathogens, weeds and animal pests effectively. In the future, biocontrol could reduce the reliance on chemical pesticide and therefore become one of the main pillars of IPM. Currently, biocontrol is not considered to be a separate principle of IPM because the current efficacy and availability of biologically based pesticides is limited to be relied on as the only pest control measure, however selection of biopesticide use in combination with IPM principles, that also have partial effects, can help to regulate pests and reduce the chemical pesticide use (Principle 6).

Some biocontrol products are already marketed in the EU (for e.g. Laminarine (brown algae) for Septoria treatment in wheat; Polyversum (*Pythium oligandrum* Drechsler) for *Fusarium* spp. treatment in cereals and maize) and numerous are under development (for e.g. *Pseudomonas* spp., *Bacillus* spp*.,* antagonists and botanicals (*Primula veris*) against late blight and Entomopathogenic fungi against wireworms in potato production) (Lamichhane et al., 2016).

Principle 6 – Reduced pesticide use

Farmers and other pesticide users, need to keep the pesticide use and other intervention approaches only at the levels that are essential. This can be done for e.g. by reducing the application frequency and doses of application. Risk of developing a pest resistance must be also considered (European Commission, 2024).

According to Meissle et al. (2009), an essential part of lowering the use and failure of herbicides is controlling weeds non-chemically with mechanical, cultural and preventive measures while the future weed population should be suppressed, and the crop yield should not be compromised. In numerous European countries (for e.g. France, Italy, Spain and Hungary), the mechanical weed control has been practiced. For instance, between the years 2000 and 2005, a political program in Netherlands has been providing subsidies and consequently 90% of conventional farms were approaching weeds mechanically.

Mechanical control of weed can also include so called pre-emergence weed control. The seedbeds are prepared some time before actual maize sowing, so as many weeds as possible can emerge and be controlled before maize emergence. The field is then mechanically cultivated by before sowing harrowing. Maize sowing is in the case often purposefully delayed. Post-emergence mechanical weed control involves in-between rows cultivation (e.g. harrowing, hoeing) and in rows cultivation (with brush-, finger-, torsion- or pneumatic weeders). Another mechanical weed control option is the flame weeding, that can take place before or after emergence of maize (Meissle et al., 2009).

Principle 7 – Anti-resistance strategies

Where there is a known risk of resistance to a crop protection product, and where pest levels require repeated applications of pesticides to crops, available resistance management strategies should be used to maintain product efficacy. This may include the use of several pesticides with different modes of action (European Commission, 2024).

Due to great cotton harvest losses, caused by high populations of insecticide resistant *Helicoverpa armigera* (Hübner, 1809) (that is an important pest also on chickpea, wheat, maize, sunflower etc.), in Egypt, Australia and Zimbabwe in 1970s and due to complete failure to control *H. armigera* with pyrethroids in Queensland in 1983, the window strategy to slowdown resistance development has been developed in Australia. The **window strategy** is divided within the growing season into 3 window stages. In this strategy, the estimated sowing time is in the middle of November.

- **Window stage I. (September – January)**

Allowed products: endosulfan, thiodicarb, *Bacillus thuringiensis* products, methomyl or chlordimeform as ovicides (to preserve the beneficial arthropod fauna and avoid infestations of mites, whiteflies and aphids)

- **Window stage II. (beginning of January – beginning of February)**

Allowed products: endosulfan or pyrethroids (max. 3 applications).

- **Window stage III. (February – April)**

Allowed products: organophosphates

Banned products: endosulfan

Later, the original window strategy became part of a bigger integrated resistance management programme (including also spatial arrangements and rotations). The enlarged window programme used today consists of 5 window stages and is also based on gained knowledge of the biology of the populations in respect to insect resistant GM cotton (Deguine et al., 2008).

<u>Principle 8 – Evaluation</u>

Based on pesticide application records and pest monitoring, the professional user should check the success of the crop protection measures applied (European Commission, 2024). Soundness of the applied crop protection approaches should be assessed (Barzman et al., 2015).

There are no estimated steps on how exactly evaluation should be done, however, Ortega-Ramos et al. (2021), suggests keeping control areas on each field to evaluate soundness of undertaken measures.

2.3. Significance of biodiversity in agriculture

Species richness, also known as biodiversity, includes all living species – animals, plants, and microorganisms, just like their habitat and the biological processes they take part in. It includes life diversity on all levels: habitat and ecosystem diversity, genetic diversity and species diversity. Biological diversity has crucial importance in fields, but consequently also greatly influences food security and human and animal nutrition. Moreover, rich biodiversity is crucial to maintain natural processes contributing to humankind's survival including fruit pollination by insect, natural pest regulation and organic matter decomposition (Čačija, 2022). Reid et al. (2005), describes in depth what benefits people get from ecosystems. So called ecosystem services are divided into four categories: water, food, wood and fibre (provisioning services); factors affecting climate, disease, wastes, water quality and floods (regulating services); recreation, aesthetic and spiritual benefits (cultural services) and photosynthesis, soil formation and nutrient cycles (supporting services). Despite people being protected from many environmental changes by culture and advanced technology, the humankind is directly dependant on the presence and circulation of ecosystem services.

Agriculture and biodiversity are inseparably connected. Protection of biodiversity cannot be narrowed down only to the preservation of natural areas, but a similar focus must be paid to the enhancement of biodiversity on agricultural lands (Le Roux et al., 2008). Therefore, agricultural policies are promoting more and more eco-oriented methods in farming to conserve natural resources and maintain biological diversity (Čačija, 2022). More than other areas of human activity, agriculture can greatly benefit from biodiversity, contribute to its conversation, or change it. Therefore, biodiversity is fundamental and of increasing importance at all levels for agricultural policy. Agriculture generally includes control and management of ecosystems in agriculturally active areas (Le Roux et al., 2008).

According to Čačija (2022), the main 4 benefits of supporting biodiversity are:

Soil quality improvement: Increased biodiversity and crop yields can be reached by various crop rotations. In soils of good quality, population growth of diverse microorganisms is encouraged, natural biological control of pathogens is being enhanced, communities of beneficial insect are encouraged to grow, turnover of nutrients is slowed down, and soil aeration and drainage are improved. Soil productivity and health can be improved by management of crop residues, crop rotations, conservation tillage, animal manure incorporation and nitrogen-fixing crops use.

Increase of insect, disease and weed control: Diverse planting can in many cases lower insect pest populations. Specialized pests typically prefer to find and stay on pure crop locations where the food income is concentrated and not interrupted. Fields that contain diverse variety of crops are typically rich in above- and below- ground beneficial pest controlling organisms, that discourage growth of diseases, supress some weeds and even promote natural defences of crops. Therefore, methods such are diverse cropping, crop rotations, scattered fields, adjacent uncultivated land and perennial crop component, can be effective in reducing pest pressure.

Support of beneficial organisms: To help stabilize pest communities, planting crops that directly inhibit insect attack or support natural enemies, shows to be efficient. Temporally and spatially diverse planting assures continuous availability of resources for populations of natural enemies. Source of habitat and food for beneficial mites, nematodes and insects can be also provided by including areas of uncultivated land and wild vegetation. Moreover, the use of ground covers and field surface residues can increase the efficiency and abundance of predators and parasitoids.

Spreading of economic risks: An opportunity to increase profits while lowering production costs is offered by farm increased diversity. Profits can be increased by adding new crops that are suitable for given climate, geography and management requirements, as it provides the opportunity to fill a gap in the market, enlarge marketing opportunities and balance out price fluctuations.

2.4. EU legislation on plant protection

The European Green Deal is a set of proposals adopted by European Commission to make the EU's climate, energy, transport and taxation policies fit for reducing net greenhouse gas emissions by at least 55% by the year 2030, compared to the levels in 1990 (European Commission, 2019). It is directly influencing agricultural sector not only by introducing the IPM (European Commission, n. d. a), but also the Farm to Fork strategy (European Commission, 2020), which aims for sustainable pesticide use.

The base promotion of sustainable use of pesticides in agriculture is the CAP (common agricultural policy), that protects agricultural crops while sustaining the yields and protecting agricultural ecosystems and health. It aims to provide safe, sustainable and healthy food for community, earn a fair and stable income for farmers, while protecting natural resources, supporting biodiversity and contributing to fight against climate change (European Commission, n. d. b).

The Farm to Fork strategy is an essential part of the European Green Deal. It aims to speed up the transition towards sustainable food system, that will have positive or neutral effect on environment, upset biodiversity loss, secure food safety, nutrition and public health, assure equal access to sustainable, nutritious and safe food, and generate fair economic returns to farmers while maintaining foods affordability and supporting fair trade (European Commission, n. d. c). Through this strategy, the EU has set itself a double target: the first goal is to reduce the overall risk and use of chemical pesticides by 50% and the second goal is to reduce use of the more hazardous pesticides by 50% by 2030 (European Union, 2023). To achieve this, a proposal for a new regulation on the sustainable use of plant protection products, that would replace the 2009 Sustainable Pesticide Use Directive (2009/128/EC), has been tabled.

The currently valid council directive 2009/128/EC (2009), states that the implementation of IPM, is to be applied by all EU farmers from 2014, so that "professional users of pesticides switch to practices and products with the lowest risk to human health and the environment among those available for the same pest problem" (Article 14.1). It is important to give priority to preventive elements. Member States shall take all necessary measures to promote low pesticide-input pest management, giving priority wherever possible to non-chemical methods (Article 14). It must be ensured that the use of pesticides is minimised or banned in certain areas (Article 12) and buffer zones of appropriate size to protect non-target aquatic organisms and protection zones for surface and groundwater used for the abstraction of drinking water, where pesticides may not be used or stored shall be established (Article 11).

In comparison to the 2009 directive, the new proposal also aims to increase the IPM implementation, use of less hazardous and non-chemical alternatives, protection of biodiversity and citizens health and to ban use of all plant protection products in specific sensitive areas (European Union, 2023).

2.5. Potato (*Solanum tuberosum* L.)

Solanum tuberosum L., known as Irish potato or white potato is after wheat, maize, and rice the 4th most produced crop worldwide and therefore a major noncereal crop produced in the world (Nascimento et al., 2023). Potato belongs to the Solanaceae family just like eggplant, pepper, tomato, tobacco, and petunia. Among the mentioned plants, potato is specific by tuber formation. The tubers are rich in starch, proteins, vitamins, and antioxidants and are formed under suitable conditions by thickening stolons (underground stems). Potatoes grow in bunches, which consist of the above-ground part (stem with leaves, flower, fruit, and seeds) and the underground part (stem base, mother tuber, roots, stolons, and daughter tubers) (Vokál et al., 2013).

2.5.1. Economic importance

The potato (*Solanum tuberosum* L.) is worldwide consumed by over one billion people, and it makes it one of the most dominant food crops worldwide. Overall, potato is currently cropped on more than 20 million ha in 150 countries and its production reaches 360 million tons. Growing of potato produces less gas emissions, than other main crops and it is a source of income for medium- and even small- sized producers. Africa and Asia are the largest potato growers, while the production in North America and Europe slowly lowers. Despite that, the lead characters of the potato global market are the EU countries together with China and South and North America. The EU countries play an important role of both – importers and exporters of potato in the world market. An expansion in potato production took place in many countries together with growth of potato products consumption. On average, an annual growth in potato products consumption extends to 1,6% which will guide to enlarged dimensions of the market up to around 440 million tons by 2030. The potato crop represents not just an important source of food but also job opportunities and income in developing countries. Nevertheless, growth of production depends on the scientific organisation of production as well as the quality of seed tubers and availability of suitable varieties that remain resistant in given climatic conditions (Mickiewicz et al., 2022).

The output rounding up to over 53 million tonnes every year, makes the EU the second biggest potato producer in the world. Furthermore, the EU dominates in the sum of consumed potatoes per head. The yearly personal consumption of every European being nearly 90 kg of potatoes, positively contributes to the size of the potato market. Consequently, potato farming represents 3,1% (around 12 billion EUR) of the total value of the EU agricultural output (Anonym, 2023).

2.5.2. Growing practices

According to Vokál et al. (2004), growing practices are key and require increased attention especially in growing systems with reduced availability of artificial fertilizers and chemical pesticides as are for e.g. organic farming systems. With correct growing practices, it is possible to achieve suitable conditions for potato crop growth and development, and acceptable yield with tubers of good quality.

Crop rotation: Root and tuber crops are the base of correct crop rotation and positively influence economic stability of the farm. Inclusion of potato growing in the crop rotation of organic systems helps to reduce occurrence of weeds and has positive influence on the soil quality, however repetitive uninterrupted growing of potato on the same field can cause overpopulation of the potato pest and diseases populations. It is recommended not to crop potatoes on the same location earlier than after 4 years after the last potato harvest. Potato is typically cropped after cereals, but clovers and alfalfa are more suitable pre-crops. Potato is a good pre-crop for cereals. It increases soil quality because of direct manuring of the crop, and the physical conditions are improved (Dvořák & Bicanová, 2007). Among potato pests that overwinter in soil and can be prevented by good crop rotation practices belong for e.g. Colorado potato beetle (*Leptinotarsa decemlineata* (Say)), wireworms (*Agriotes* spp.), late blight (*Phytophthora infestans* Mont deBary) and early blight (*Alternaria solani* Sorauer) (Alyokhin et al., 2013; Adolf et al., 2020; AHDB, 2021).

Choice of location: The best soils for potato cropping are loose, well-drained, with low content or no lumps or stones and rich in nutrients (for e.g. sandy loam) in the opened locations (fast soil and plant drying after heavy rains helps to minimize the late blight outbursts). Slope of the field should not be more than 8%. Preferred soil reaction is between pH/KCL 5,5 – 6,6 (Dvořák & Bicanová, 2007).

Choice of variety: In systems with low artificial and chemical input, varieties with shorter vegetation time are preferred to avoid pest population growth. In case of long vegetation potato crops (harvested in late summer/early autumn), varieties with increased resistance towards late blight should be chosen (Dvořák & Bicanová, 2007).

Seed choice: Constantly renewing availability of high-quality planting material is the basis of successful sustainable potato production as it directly affects the yields. As a vehicle for important viruses, the seed faces frequent degeneration, which is the most common reason for drops in productivity, quality and health of yield. As there are various types of seed insecurity (lack of availability, limited access to high quality seed, poor seed quality etc.), extensive research is being performed to improve access to quality seeds for small farmers, especially in 3rd world countries (Devaux et al., 2020).

In the council directive 2002/56/EC (2002), it is explained that the use of appropriate potato seed assures greater potato crop health and therefore also productivity. According to this directive, potato seed should only be allowed to be marketed after official examination and certification. The evaluation includes evaluation of the health of potato crops in the fields, potato seed health, appearance, quality and integrity.

Seed preparation: The seed tubers quality and health should be observed and spoiled tubers must be eliminated. Pre-germination (biological preparation) of the seed tubers the damage caused by late blight can be reduces and the mineral content and skin firmness increased. Pre- germinating takes place 6 weeks before sowing under this procedure: First 10 days seed tubers are left in dark at the temperature between 8 and 12°C. After the first sprouts are formatted, tubers are slowly illuminated, and temperature is increased to 12 – 18°C. One week before sowing, the tubers are left under the temperature between 6 – 10°C. This procedure can be simplified and shortened to sprouting by leaving the seeds at the temperature of 8°C for 3 weeks, during which the tuber develops 5 mm long sprouts (Dvořák & Bicanová, 2007).

Soil preparation: The number one irreplaceable tillage approach is the stubble, which maintenances soil moisture and encourages weed seed germination (to allow and simplify its destruction in the next steps). Next key soil measure is the tillage, that incorporates after harvest debris, manure and green manure. In spring, the ground-based skidding and dragging encourages the early spring weed germination. Before sowing, soil loosening takes place into the depth of 15 – 18 cm (Dvořák & Bicanová, 2007).

Sowing: Potato is cropped in rows with the distance of 75 cm to ensure good airing and lower humidity between the plants. Seed tubers are planted into trenched rows and covered with trenching-leftover soil until small hills are formed. Optimal count of plants in 1 ha is 40 000, but with early varieties, it can be up to 53 000 plants/ha. Seed tubers are sowed at the temperature of 8°C (sprouted seed tubers already at 6°C). Potato may never be planted into wed/muddy soil (Dvořák & Bicanová, 2007).

Fertilization: Potato crops are mainly fertilized with manure, green manure and compost. Fertilizing with potassium and phosphorus may be applied after soil analysis (Dvořák & Bicanová, 2007).

Harvesting: Ploughing out of tubers is optimally done at when the temperature is lower than 5°C or higher than 20°C. Tuber damage and cutting must be avoided while harvesting (Dvořák & Bicanová, 2007).

2.5.3. The most important pests (overview)

2.5.3.1. Colorado potato beetle (*Leptinotarsa decemlineata* (Say))

Colorado potato beetle (CPB) is known as the biggest potato pest worldwide (Göldel et al., 2020). According to biological classification, the Colorado potato beetle *(Leptinotarsa decemlineata* (Say)) belongs to the Chrysomelidae family, which is the third largest group of the order Coleoptera (beetles) (Alyokhin et al., 2013a).

Morphology

The body of an imago CPB is robust and has oval shape (Figure 2.2). It can be up to 10 mm long and up to 7 mm wide. Its colour can vary from pale yellow to yellow-orange, with 5 brownish or black longitudinal stripes on each elytron and irregular markings of the same colour on the thorax. The head is small with 2 compound eyes on its side and an antenna, which are shorter than its body. The eggs have yellow to orange colour, oval shape, and can vary in size from 0,8 to 1,5 mm. Larvae are orange to red in colour with a small black coloured head, small legs, and 2 rows of black dots along the sides of their body. The size of larvae reaches up to 15 mm. (Capinera, 2001; Weber, 2003; Wale et al., 2008; Alyokhin et al., 2013a; Waters & Jensen, 2014).

Life cycle

This pest commonly overwinters as an adult in soil in depths between 10 and 40 cm. One female beetle can produce between 300 and 800 eggs in its lifetime. The eggs can be found in clusters of 20 - 40 pieces on the bottom side of potato leaves. The development of embryos is dependent on the temperature. At the average temperature of 20°C larvae hatch on average of 10 days. Within three to four weeks, the larvae undergo 4 instars. At the end of 4^{th} instar, the larvae move into 5 – 12 cm depth of soil to pupate. The pupa state lasts approximately 14 days, after this time, the imago hatches (so-called summer beetle) and under good conditions becomes the base of 2^{nd} generation (Capinera, 2001; Weber, 2003; Wale et al., 2008; Alyokhin et al., 2013; Waters & Jensen, 2014). Typically, the CPB has 1 generation in colder climate and 2 generations in warm climates (Hausvater & Doležal, 2013).

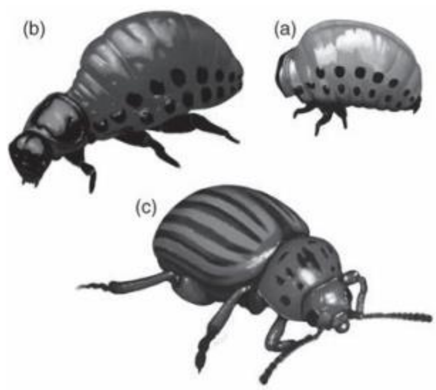

Figure 2.2. Colorado Potato Beetle: young larvae 1.-2. instar (a), older larvae 3.- 4. instar (b), imago (c) (Waters & Jensen, 2014).

Damages

When the population of the CPB is not controlled on time, it can cause a complete defoliation of plants and therefore serious yield losses or plant death. Most endangered are early-potato areas, where the beetle has a greater chance of creating a 2nd generation (Vokál et al., 2004).

Hausvater & Doležal (2014a) state, that the CPB causes loses of 10% at approximately half of all the potato fields in the Czech Republic (i.e. 15 000 ha). The average yield loss is 2,5 t/ha and the economic loss comes to 138 EUR/t. By proper implementation of the IPM practices in the Czech Republic, the 10% loss could be reduced to only 5% loss. Igrc Barčić et al. (1999) proved that the yield reduction caused by CPB depends on the percent of the defoliation and on the time when defoliation occurred: if the total defoliation occurred at the beginning of tuberization the yield on untreated plots was 8.8 times lower than the yield on the protected plots. When total defoliation occurred shortly before the end of tuberization the yield was only 1.4 times lower on unprotected than on protected plots. When 75% defoliation occurred during an intensive tuberization process the yield on unprotected plots was 2.5 times lower than on protected plots.

Management

Prevention: The CPB may be well managed by crop rotation under the condition that the distance between potato fields is more than 0,5km. Crop rotation and trenching significantly reduce pest spreading as CPB disperse by walking, that is made difficult by these approaches. Implementation of mulching on potato plots shows good results in lowering the density of the CPB populations as it creates habitat for natural enemies. Removal of after-harvest debris can negatively influence next population growth of the pest (Alyokhin, 2009). According to Bažok et al. (2022), by early potato planting and use of short maturing varieties, plants can be ready for harvest before the 2nd generation of CPB starts. By tilling, the population of the pest can be reduced. Intercropping of potato with onions (*Allium cepa* L.), French marigold (*Tagetes patula* L.), tansy (*Tanacetum vulgare* L.) horseradish (*Armoracia rusticana* G. Gaertn., B. Mey. & Scherb) and Bush beans (*Phaseolus vulgaris* L.) is a very effective approach as these crops produce excessive volatiles that can confuse the pest by covering up potato chemical emissions.

Mechanical and physical control: On small agricultural units CPB can be mechanically collected – manually or with pneumatic devices. Pneumatic heat machines, propane flames or bio collectors can also control beetles' population. Establishment of physical and mechanical barriers can delay the population growth (Bažok et al., 2022).

Biological control: To control overwintering adult forms, entomopathogenic nematodes can be efficient. Under favourable conditions (avoiding high temperatures and draught), spraying of fungi *Beauveria bassiana* against adults and larval stages has been proven to be efficient method of control. Bacterial insecticides based on the entomopathogenic bacteria *Bacillus* *thurigiensis* var*. tenebrionis (Btt)* are effective control of early larval stages. Pyrethrin, spinosad, azaridachtin and abamectin have been proven to be highly effective just like chemical control, however CPB has the ability to develop resistance rapidly ant therefore they may not be overused (Kroschel et al., 2020; Bažok et al., 2022). The aim of **conservation biological control** is to enhance and maintain naturally occurring natural enemies, predators and parasitoids. It is based mostly on cultural practices that provide food and shelter for e.g. establishing flowering strips, grass strips and forbs (Bažok et al., 2022).

Chemical control: This pest has a good ability to develop insecticide resistance, which makes its control exceedingly difficult. It has developed resistance to almost 40 different types of chemical pesticides. Despite the possibility of prevention of CPB occurrence by well-chosen agrotechnical measures, most farmers currently rely on chemical insecticide use. (Alyokhin, 2009; Opatrný, 2012). Carbamates, organophosphates**,** neonicotinoids and pyrethroids are used in chemical control (Alyokhin et al., 2013b.) According to EU Pesticide database (2024), in the EU are currently allowed only few synthetic pesticides from above mentioned groups: formetanate, pirimicarb, (carbamates); malathion, pirimiphos-methyl, (organophosphates); acetamiprid (neonicotinoids); tefluthrin, cypermethrin, deltamethrin, tau-fluvalinate (pyrethroids).

According to Alyokhin (2009), no 100% effective method against the CPB has been discovered until today. So far, the most efficient way farmers have is combination of available methods (Alyokhin, 2009).

2.5.3.2. Wireworms (*Agriotes* spp.)

Wireworms are common pests in mild climates. They typically occur in arable fields, gardens and especially in old permanent pastures in Europe, North America and Asia. Among *Agriotes* spp*.* Belong over 39 species that attack potato tubers, however there are three species, that are responsible for the majority of agricultural harm in the UK and by conventional means are not distinguishable or differentiable. These species are*: Agriotes linneatus* (L.), *Agriotes obscurus* (L.) and *Agriotes sputator* (L.). They are soil-inhabiting, larvae of click beetles (Coleoptera: *Elateridae*). However, in Croatia and in surrounding countries, the most significant economic loses are caused by different species of the *Agriotes* genus. These are: *Agriotes brevis* Cand., *A. lineatus* (L.), *A. obscurus* (L.), *A. sputator* (L.), and *A. ustulatus* Schall. The main host of wireworms are grasses, nevertheless they also frequently attack potatoes, carrot, asparagus, sugar beet and leek (Kozina et al., 2015; Kroschel et al., 2020; AHDB, 2021).

Morphology

The body of an imago is 8-15 mm long and 2-3 mm wide, it has brown-to-black colour, with fine white-grey hairs all over their body (Figure 2.3.). Newly hatched wireworms are colourless and 1,3 mm long, over time the colour changes to shiny golden-brown and they grow up to the length of 25 mm. Body of the larvae has hard skin, cylindrical shape and two dark spots at the tail (Figure 2.3). The head is dark brown with strong mouthparts and by the head 3 pairs of legs are located (Kroschel et al., 2020; AHDB, 2021).

Figure 2.3. Adult click beetle (left) and larvae (right) – wireworm (AHDB, 2021).

Life cycle

The adult beetle lives approximately 1 year and overwinters bellow the soil surface. Larvae (wireworms) hatch from eggs laid by females just below the soil surface. The larvae stage lasts 4-5 years and lives underground (Kroschel et al., 2020; AHDB, 2021).

Damages

The larvae of *Agriotes* spp. can cause severe damage on tubers in potato fields. Damaged potato tubers have small round holes on their surface that continue into narrow tunnels. Even at low populations, they can significantly reduce the potato tuber marketability and overall reduce the market value. Moreover, this tunnelling is responsible for creation of an entry for some pathogens and consequently rotting of tubers. Wireworms became more significant pest after prohibiting the organochlorine-based insecticides. Aside of potato, wireworms attack a variety of crops for e.g. maize, wheat, sugar beet and carrot (Keiser et al., 2012; AHDB, 2021; Booth et al., 2022).

Management

Monitoring can prevent wireworm damages by identifying wireworm invaded fields and consequently planning risk assessing approaches such are soil sampling at each field and establishment of pheromone and bait traps (Kroschel et al., 2020). If damage is expected, and the crop allows it, an early harvest can be considered to avoid loses (AHDB, 2021).

Cultural practices: As soil borne wireworms are feeding on roots of various crops a proper weeding can positively contribute to population suppression and by proper ploughing and crop rotation with crops that need frequent tilling (Kroschel et al., 2020). During ploughing, the desiccation sensitive wireworm eggs get to the surface and die, just like larvae that become a better target for bird predation. Ideal time for ploughing can be estimated by monitoring the population growth with bait traps (Poggi et al., 2021).

Biological control: The use of natural enemies against wireworms is currently under research. In past years, various experimental inundative releases of natural enemies have been performed and, in the future, they could be a way for wireworm control. Currently, the main research focuses on entomopathogenic fungi naturally occurring in soil *Metarhizium anisopliae* (also known as *M. brunneum*), which is showing the most promising results, and some research is also being performed on entomopathogenic nematodes (Kroschel et al., 2020; Catton et al., 2021; Poggi et al., 2021).

Biocidal meals: An effective way to control wireworms in the future could be biocidal meals implementation. In laboratory and pot trials, seed meals of *Brassica carinata* (A. Braun) have caused mortality of the larvae higher than 80% (Poggi et al., 2021). In Italy, successful on-field research confirmed, that if sowed under certain conditions, defatted seed meal of *Brassica carinata* can control wireworms just as effectively as chemical insecticides. Conditions that need to be met for its efficient use are sufficient glucosinolate concentration in the seed meal, even distribution; immediate incorporation into 20cm depth, soil temperature between 10,5 and 16°C, enough moisture (might require irrigation), and presence of the pest near the soil surface when applying to assure direct contact (Catton et al., 2021).

Chemical control: Sometimes it is required to apply and incorporate insecticide into soil when the crop is planted, to control wireworm populations during the cropping season (Kroschel et al. 2020). In past decades, insecticidal organochlorines, organophosphates and carbamates have been used to control (not only) wireworm populations. In last twenty years, various chemical seed treatment for e.g. pyrethroids, neonicotides and phenyl pyrazoles, were predominantly used to protect sunflower crop. This treatment did not assure death of wireworm larvae, but it did have a repellent effect (Gvozdenac et al., 2022; Nikoukar & Rashed, 2022). According to EU Pesticide database (2024), in the EU are currently allowed only few synthetic pesticides from above mentioned groups: tefluthrin, cypermethrin, deltamethrin, tau-fluvalinate (pyrethroids); acetamiprid (neonicotinoids).

2.5.3.3. Late blight (*Phytophthora infestans* Mont deBary)

The late blight is a plant disease caused by *Phytophthora infestans* Mont deBary, which was previously classified as a fungus because of its superficial similarity to filamentous fungi but is now classified as an oomycete in the Stramenopiles kingdom (Adolf et al., 2020). *P. infestans* is worldwide the most feared disease in both – ecological and conventional potato and tomato *(Solanum esculentum* L.) production. Under certain conditions such are mild temperatures and high humidity, can late blight terminate a full field in few days. For its suppression, an exact and accurate approach and well-chosen measures are required as *P. infestans* is an easily proliferating pathogen, which can (on less resistant varieties) produce up to 300 000 sporangia every 3 – 5 days. Under unfavourable conditions, sporangia can be washed down from the leaves into the soil and infect potato tubers (Fry & Goodwin, 1997; Mayton et al., 2001a, 2001b; Döring et al., 2006; Mayton et al., 2008; Adolf et al., 2020) or carried away by wind to a distance of several kilometres away from the origin of the infection, where they can infect other potato fields (Aylor et al., 2001).

Life cycle

P. infestans is able to reproduce both – sexually and asexually. During sexual reproduction, very durable oospores (that stay in soil during the non-vegetative periods) are created (Fry & Goodwin, 1997; Fry et al., 2013). Asexual reproduction takes place through sporangia found in soil, contaminating the potato tubers. Migration and spreading of sporangia happen with wind and rain (Aylor et al., 2001). Durable sporangia of *P. infestans* can survive in the soil even several years (Alkher et al., 2015). This organism produces several generations during one season and adjusts quickly to current environmental conditions as the population is able to select and reproduce the most resistant strains to fungicides and to resistant barriers of the host (Vokál, 2013).

A common source of the late blight, that is unnoticeable by naked eye, are contaminated seed tubers, as *P. infestans* can overwinter on them. Mycelium of this pathogen starts to grow into green parts of the potato plant right after the young potato plants start to develop. Plants developed from infected seed tubers are considered the primary source of infection. The infection is further spread by wind which can cause an epidemy (Hausvater & Doležal, 2014b). Asexually formed sporangia that are carried away by wind, are typically the main cause of most devastating late blight epidemic outbursts in potato production. After landing on plant surface, sporangia can germinate directly or form zoospores that later encyst, germinate and penetrate the host plant tissue. At this stage, the infection is not noticeable by naked eye, however molecular interactions already take place inside the plant cell. After penetration of the cell, haustoria that secretes effector proteins are being formed. At this stage of development, the living plant cell is necessary for *P. infestans* to gain nutrients from (Adolf et al., 2020).

Symptoms and damages

Within 2–3 days after infestation, when the pathogen switches to the necrotrophic stage, first visible symptoms appear (Figure 2.4.). Lesions on the leaves are light to dark brown in colour, waterlogged, with no regular shape, sometimes surrounded by a yellow halo and not bounded by leaf veins. The first symptoms typically begin to develop where water accumulates – near the leaf tips or margins and in stems near the petioles. Affected tubers show irregular, slightly depressed areas of brown colour. In cross section, finger-like extensions can be seen from the outer surface to the centre of the tuber (Adolf et al., 2020).

The economic and social thread that *P. infestans* represents is best shown on its crucial role in well-known Irish Famine of the mid-19th century when millions of people died or were forced to emigrate as a result of a late blight epidemy outburst. Nowadays the late blight continues to be a problem in potato production worldwide. It is responsible for major annual losses that have been estimated to be about €6.1 billion, with serious further consequences in food security, for the most part in developing countries (Adolf et al., 2020).

Management

Prevention: Reduction of humidity and improved air circulation can prevent the illness outburst. It is important to watch and maintain health of the seed tubers. Keeping good hygiene during harvest and storage. Some potato varieties with higher resistance are on the market (Bažok et al., 2022).

Mechanical protection: Mulching and trenching (hilling) acts as a filter and prevents the transfer of late blight spores from the upper part of the plant into the soil to the tubers, that typically happens during rainfall. Shallowly placed tubers (insufficiently covered with soil or mulch) are more easily attacked infected (Döring, 2006; Dvořák et al., 2014).

Early vegetation termination: An early (or artificial) termination of vegetation of potato is done before natural death caused by late blight (Hausvater et al., 2021). In case of invasion between 1% - 20% (it is better to stick with the lower limit) it is recommended to end the vegetation artificially, especially if rapid spreading is expected for e.g. when intense rainfall has been announced (Vokál et al., 2004; Dvořák et al., 2014).

Copper control: Copper plant protection products can be applied in organic plant protection. Application should take place before rain, if infection is expected (Bažok et al., 2022).

***Pythium oligandrum* M1:** An oomycete, (that is the active ingredient of for e.g. Polyversum, Biogarden and Polydresser), which is used for seed tubers treatment. It is classified as growth promoter, but also protects plants from different pathogens. *P. oligandrum* has excellent results in control of *Phytophthora* spp. (ÚKZÚZ, 2022; Wang & Long, 2023).

Chemical control: The use of fungicides remains to be the most efficient control. Typically, the fungicides with broad control are used. The main groups are products based on chlorothalonil (e.g. Bravo or Echo) and ethylene bisdithiocarbamate (EBDC, e.g. Dithane or Penncozeb) (Miller et al., 2018). Other examples fungicides used for control of both – late blight and early blight are: maneb, mancozeb, chlorothalonil, triphenyl tin hydroxide (Adolf et al., 2020).

Figure 2.4. Late blight on potato leaves. (available from: https://www.apic.cz/9302-ukzuz-spustil-novou-prognozu-plisne.ht)

2.5.3.4. Early blight *(Alternaria solani* Sorauer*)*

Early blight is after the late blight second most important potato crop illness, found in majority of potato-producing countries, although it has also been spotted on other crops such as tomato (*Solanum lycopersicum* L.), hairy nightshade (*S. sarrachoides* Sendt), eggplants (*S. melongena* L.), horse nettle (*S. carolinense* L.), black nightshade (*S. nigrum* L.), pepper (*Capsicum* spp.*),* and non-solanaceous weeds. The leading pathogen to cause this disease on potato is fungus *Alternaria solani* Sorauer. Nevertheless, it has been discovered, that some other large-spored *Alternaria* spp. have been causing this disease as well. For instance, in certain regions of Brazil, early blight caused by *A. grandis* Simmons and by *Alternaria protenta* in Algeria rather than by *A. solani* has been reported. Moreover, in Belgium an early blight outbreak has been reported caused by all three mentioned *Alternaria* spp*. (A. grandis, A. solani* and *A. protenta).* The early blight symptoms are indistinguishable by naked eye between the three above mentioned *Alternaria* spp. (Adolf et al., 2020).

Life cycle

The *Alternaria solani* is overwintering in the soil and/or dead plant material left on the field in the form of conidia, mycelium or chlamydiospores. The primary infection occurs in spring through conidia carried by rain splashes from the soil to the oldest (lower) leaves. This pathogen penetrates the leaf tissue through stomata, wounds or intact epidermis. First necrotic foliar symptoms are visible within 2-4 weeks after the potato crop emergence. In the necrotic lesions the formation of conidia takes place at the optimal temperature of 20°C but they can be formed at the temperature spectra between 5°C – 30°C. Formed conidia are spread by wind onto surrounding stems and leaves where it stays in a latent form for about 3 – 7 days. Once the plant reaches certain age and under infection favourable conditions, the middle and upper leaves get very quickly colonised by *A. solani.* Typically, the most favourable condition for infection development is when the leaf wetness last 8+ hours and temperature conditions above 22 °C. Alternation of dry and wet periods are also favourable for early blight development. In general, older plants are more vulnerable to getting infected (Adolf et al., 2020).

Symptoms:

Initial symptoms of the early blight are visible by naked eye on the older leaves of the plant in the form of necrotic spots and for several weeks the pathogen does not spread to upper leaves (Figure 2.5). Dark brown – black foliar necrosis, starting from the bottom (the oldest) leaves are typical symptoms caused by *A. solani*. In contrast to *P. infestans* causing the late blight, the early blight symptoms typically appear very shortly (few weeks) after infection under favourable conditions and are often limited by leaf veins and therefore angular in shape. Starting symptoms of early blight appear as dark brown few millimetres wide dot shaped necrosis and over time the lesion grow to overtake the whole green leaf area in multiple necrotic spots with the diameter up to 2 centimetres. The boarders of necrotic spots can turn get chlorotic due to activity of mycotoxins and turn in yellow colour, eventually the chlorosis can expand to the whole leaf. After the necrotic spots enlarge onto the full leaf area, the necrotic leaf falls off and become a source of the disease in the soil and infection of tubers. When the conidia of *A. solani* are washed down from the leaves by rain, tubers get also infected. Infected tubers have slightly sunken and dark in colour lesions. Dry – hard rot lesions on tubers not only cause storage loses but also reduce quality of table potatoes and lower germination ability of seed tubers. The progression of early blight development is directly dependant on the crop growth stage, weather conditions, short crop rotations, potato cultivar and concentration of conidia in soil/ surrounding fields (Adolf et al., 2020).

Figure 2.5. Initial and advanced foliar symptoms of early blight (Adolf et al., 2020).

Management

Prevention: Maintenance of healthy seed tubers, proper hygiene during harvest and storage. Choice of resistant varieties (Bažok et al., 2022). By proper crop rotation (avoiding rotation of potato with other host plants e.g. tomato) and treating of host plant weeds (for e.g. black shadow) we reduce the chance of infection. On the other hand, intercropping with biofumigant plants (for e.g. leaf radish and white mustard) reduces the disease growth. Another risk reducing approach is removing and burning after harvest debris (Adolf et al., 2020).

Harvest, tuber health: The pest cannot enter tubers with unharmed periderm. By avoiding wounding during harvest and only harvesting fully ripe tubers (with smaller chance to be wounded) we decrease the chance of seed contamination. Seed tubers that are not affected by other pests and diseases are less likely to be affected by early blight (Adolf et al., 2020).

Compounds with proven efficacy: In organic agriculture, seedlings can be treated with copper hydroxide-based plant protection products (Bažok et al., 2022).

Resistant cultivars: Potato varieties with increased early blight resistance are available on the market (Adolf et al., 2020).

Chemical control: The use of fungicides remains to be the most efficient control. Typically, the fungicides with broad control are used, just like in control of late blight. The main groups are products based on chlorothalonil (e.g. Bravo or Echo) and ethylene bisdithiocarbamate (EBDC, e.g. Dithane or Penncozeb) (Miller et al., 2018). Other examples fungicides used for control of both – late blight and early blight are: maneb, mancozeb, chlorothalonil, triphenyl tin hydroxide (Adolf et al., 2020).

3. Materials and methods

3.1. Description of the area – County of Međimurje

County of Međimurje is located at the northernmost part of Croatia on the Hungarian and Slovenian border (Figure 3.1.). With the surface of the area over 729.25 km^2 it is the smallest County of the Croatian republic (1,29% of the Croatian territory). The climate conditions of this area are favourable for production of almost all agricultural crops typical for the moderate continental climate, especially maize, potato, vegetables and industrial plants. The largest part of the arable area in the County is covered with cereals (Golubić et al., 2019). However, potato growing in Croatia is usually organised on privately owned farms on small fields and Međimurje is one of the regions with biggest potato production (Poljak et al., 2009).

Majority of the farms (12) are located in the town Belica, the remaining two are in Mursko Središće and Podturen.

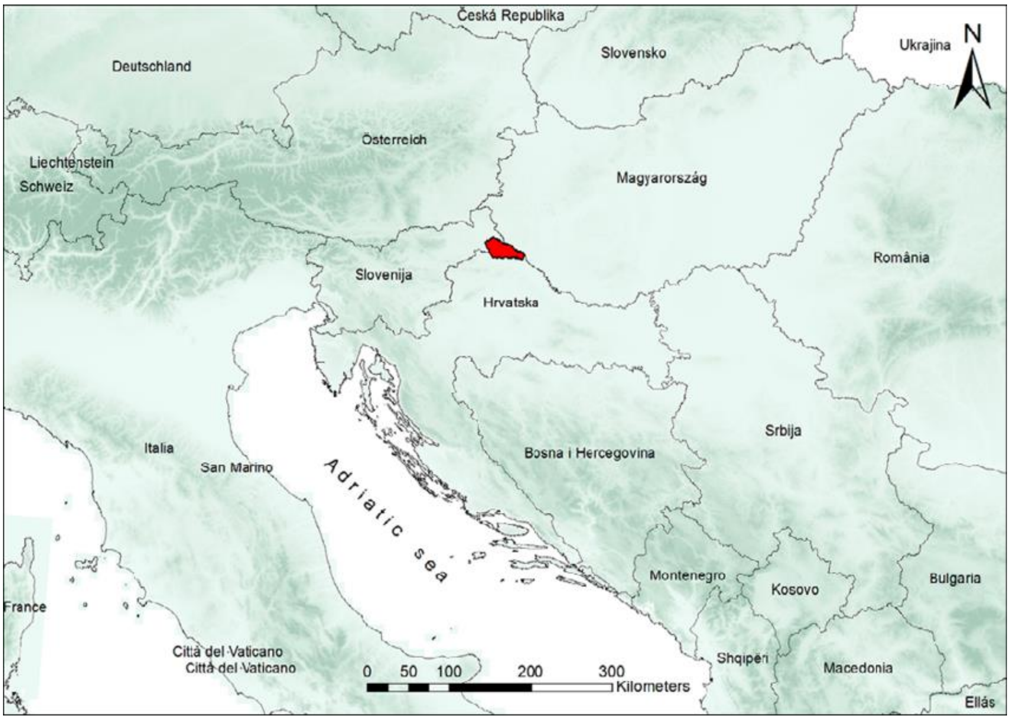

Figure 3.1. The position of the Međimurje County on the map of the Republic of Croatia (avaiable from: https://www.researchgate.net/figure/Geographical-location-of-Medimurje-County_fig1_372375629)

The sum of agricultural land area in Međimurje is about 30 000 ha from which the area of arable land takes about 26 000 ha. The overall area of potato production in Croatia, depends on given year and comes up to 8 000 – 9 000 ha. The average potato yield in Croatia is 15,9 t/ha and according to some sources, around 60 % of the Croatian potato production takes place in the Međimurje County (Ministarstvo Poljoprivrede, 2021) as it is illustrated by the Figure 3.2.

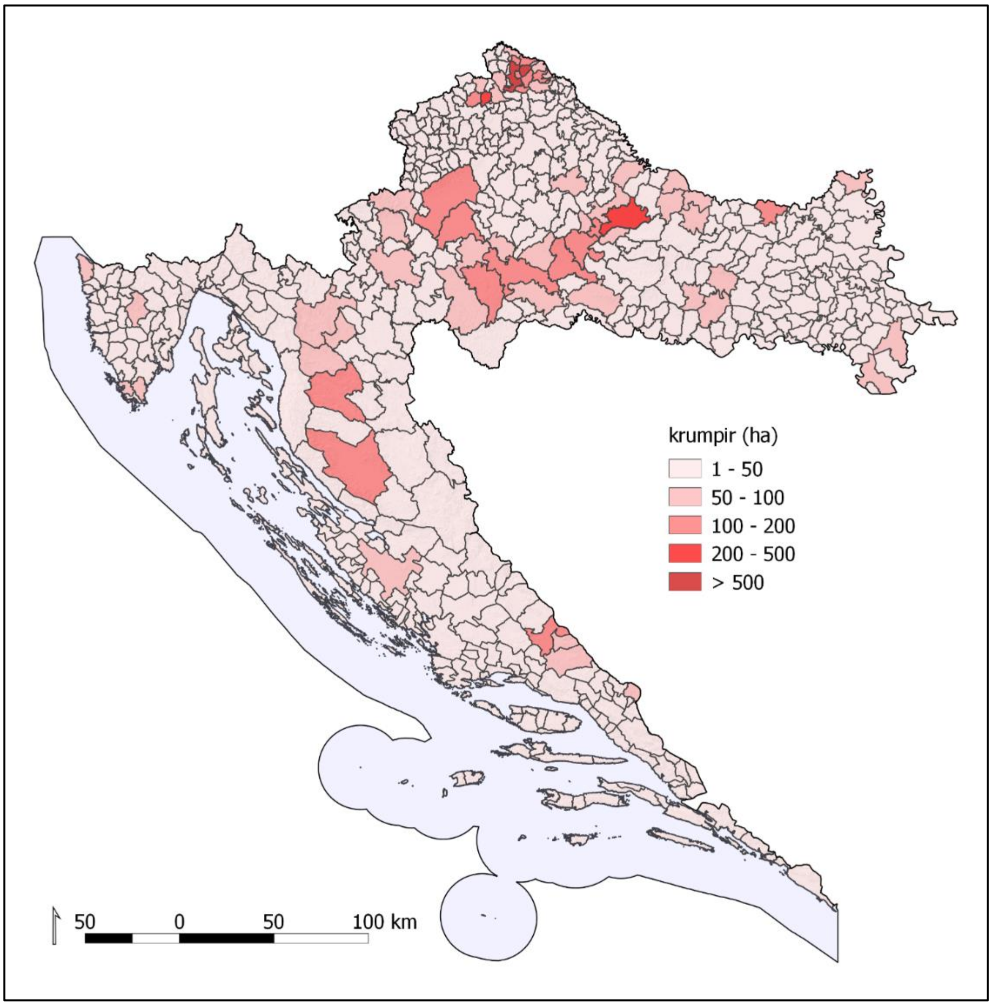

Figure 3.2. Distribution of potato production in Croatia in 2017 (source: Ondrašek et al., 2019)

3.2. Description of questionary and its implementation

To gain an insight into Croatian potato farmers current situation and to collect data from farmers of the Međimurje county, regarding their potato production systems in years 2021, 2022 and 2023, a Google form in English has been created. This questioner-type survey consists in total of 30 questions. The questions were created based on a thorough knowledge of the topic and after extensive literature research. The questionnaire gives a brief overview of the general potato production systems in terms of size, management and ownership of the farm, as well as the frequency of potato cultivation and the varieties grown. The key questions of this form focus on the main potato pests (rodents, insects and diseases) and their chemical or biological control, as well as the integrated pest management (IPM), organic and artificial fertilization and soil management practiced on the potato farms. The last two questions relate to current technical problems and the support needed to implement more biological pest control measures.

Most of the questions in the questionnaire are structured multiple-choice questions. In most cases, structured questions with undisguised objectives are asked. This ensures standardization of the procedure and simplifies data processing. A small number of the questions contains open questions.

The survey has been translated into Croatian, inserted into a word document and printed. This allowed data collection face-to-face in a direct conversation between the interviewer and the respondent and ensured the highest accuracy of the data. All data have been collected personally on the 2nd of February 2024 in the Međimurje county. Final number of questioner respondents is 14 farmers. Collected data have been translated back into English and inserted into the Google form for easier analysis.

At the beginning of the questioner, aim of the survey has been explained, respondents were informed that their personal information will not be exposed, and that collected data will be presented anonymously. The questioner itself consists of two parts. Part A of the questionary collected personal information of respondents and their contact details and were not used for analysis. Data from part B have been used for analysis and are available below. The questionary is attached as an appendix in the 8th chapter.

3.3. Data analysis

The results have been converted into an excel document and were analysed manually. The graphs and tables were created also using the excel program. Descriptive statistical tools such as mean, median and mode were applied for data analysis.

4. Results

Out of 14 farmers, three grow potatoes on their own fields (Figure 4.1). The remaining 11 are grown on fields that are a combination of owned and leased land.

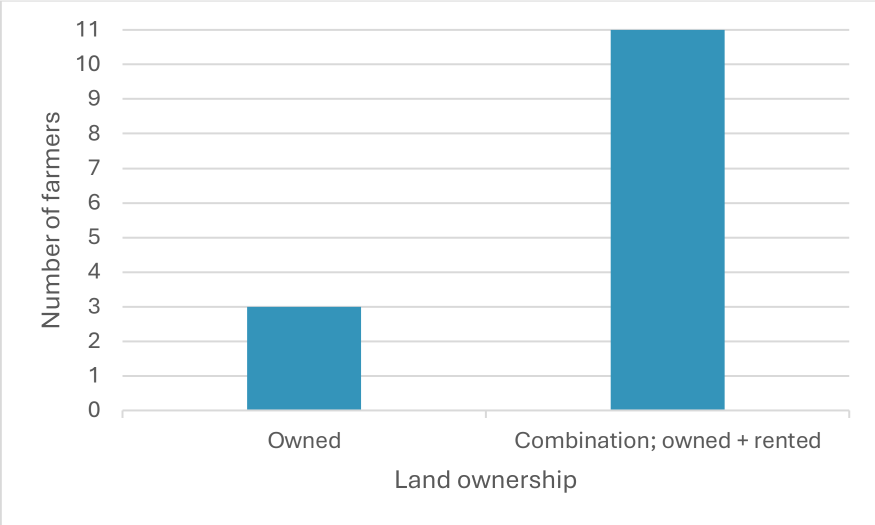

Figure 4.1. The structure of farms regarding the farmland ownership

Majority of the questioned farmers, 13 respondents, have an individual (family) farm and only 1 respondent is part of a company (not partnership) with profit objectives.

Differences in the level of education were observed. From our sample group, four farm managers (29%) have no education related to agriculture, seven farm managers (50%) have completed high school, and only three farm managers (21%) have a university degree (Figure 4.2).

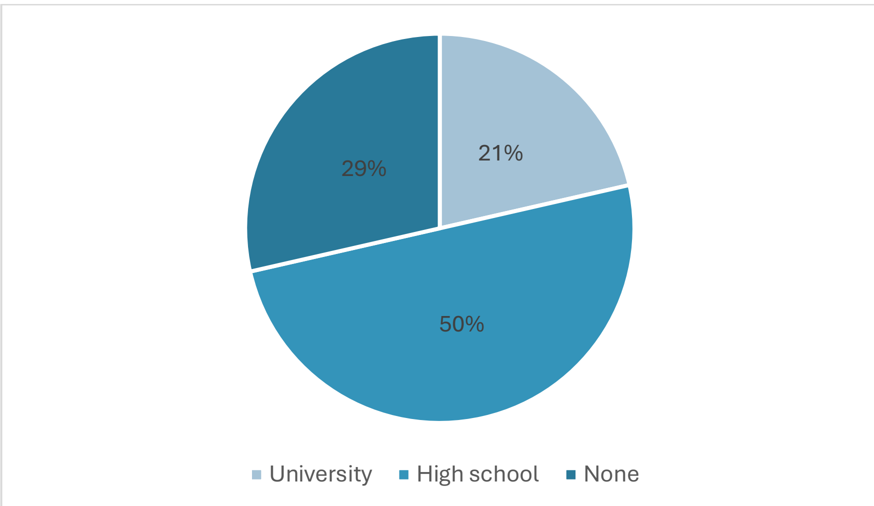

Figure 4.2. Educational level accomplished by the farm managers shown in %

Unlike educational level, in terms of farming experience, the results were very consistent, with all farm managers having 10 or more years of farming experience.

Differences were observed in the total size of the farms. The size of arable lands on most of the farms (nine) is between 10 and 50 ha, while three farms have more than 50 ha and two farms less than 10 ha of arable land in total (Figure 4.3.). The average arable area is 37 ha.

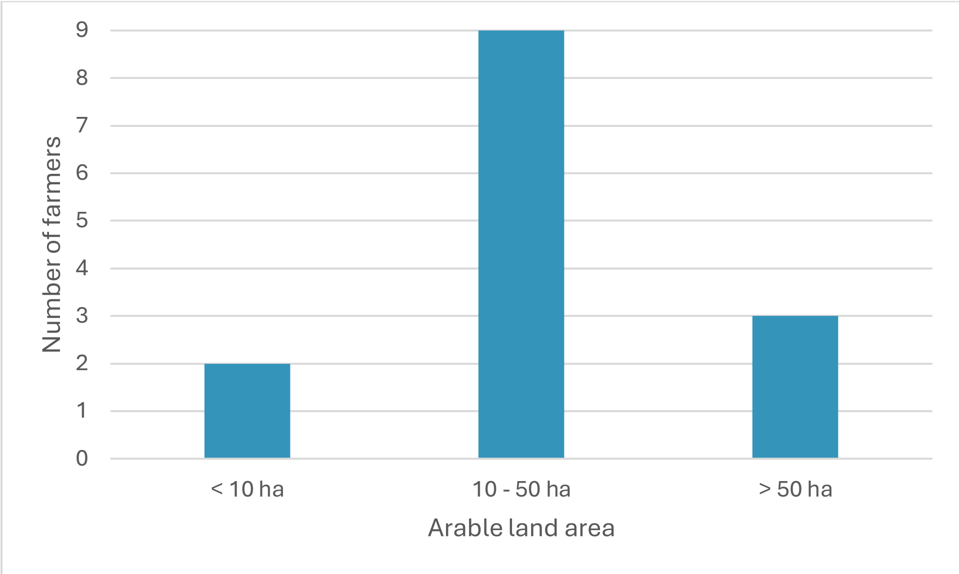

Figure 4.3. Arable land area of interviewed farmers

In comparison to overall arable area, the sizes of potato production area were significantly smaller. The most farmers (seven) produce potato on 20 – 23 ha, five farmers produce it on 5 – 12 ha and two farmers produce potato on less than 5 ha (Figure 4.4.). The average potato producing area is 13 ha.

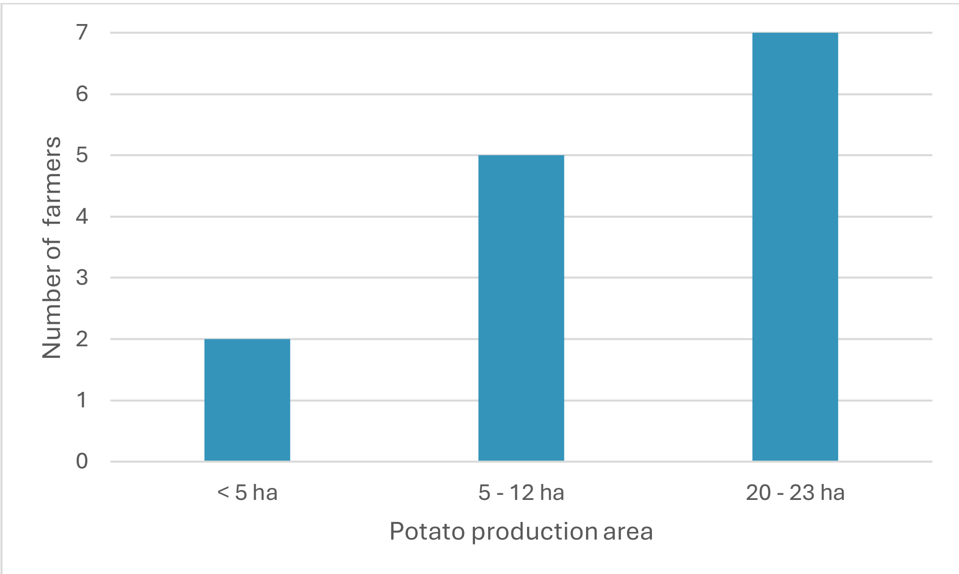

Figure 4.4. Potato production area of the farms

In the following figure 4.5. it is shown what is the difference between the production area of potatoes and the production area for other crops on each farm.

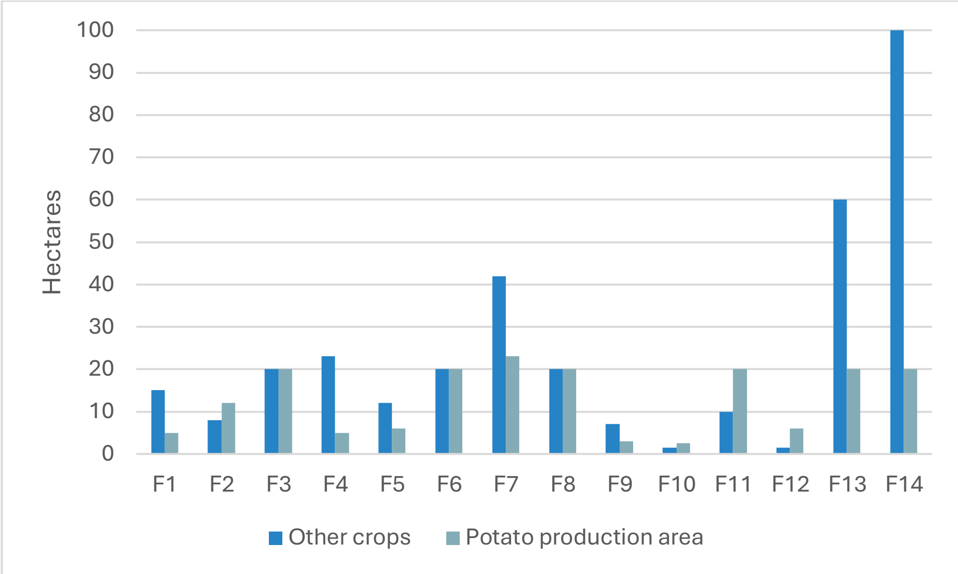

Figure 4.5. Comparison of production area of potato and other crops

In Figure 4.6. it is shown what is the % share of the area for potato production in the total area of arable land on each farm.

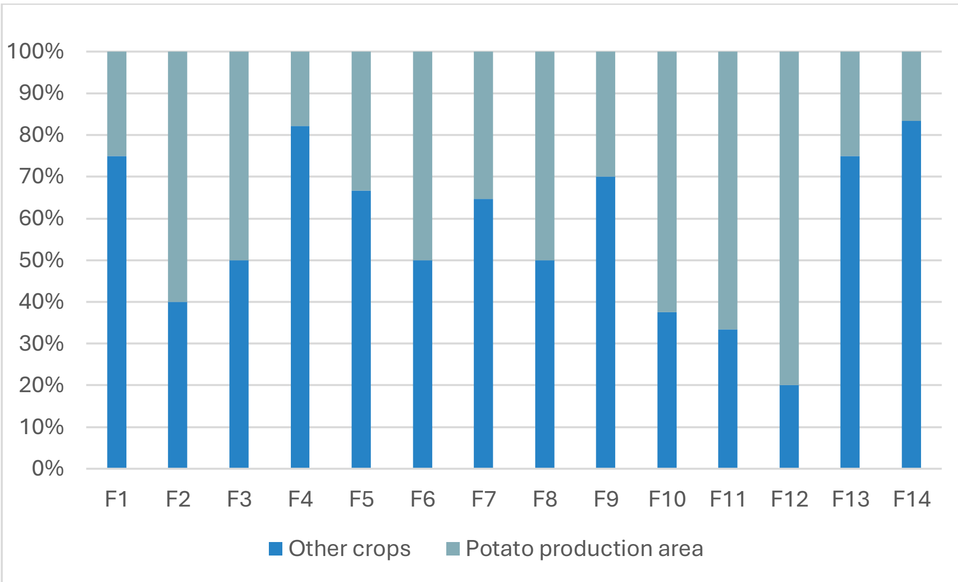

Figure 4.6. Comparison of production area of potato and other crops in %

All responding farmers grow potatoes for human consumption.

From our respondents, only one has a Demeter certification. However, farm is not managed in the system of biodynamic agriculture due to various reasons. All other thirteen farms do not have any specific certification and are managed in the system of conventional (i.e. integrated) production.

None of our interviewees keep commercial livestock on their farm and therefore do not have their own source of manure that could be used for fertilizing potatoes.

On all the examined farms, except for potatoes, most cereals are planted (wheat, corn and triticale). One farm produces butternut squash, and one farm grows sunflowers.

Differences were observed in number of fields for potato production. On one farm potato is grown on less than five fields. On three farms the number of fields with potato production is between five and ten, on four farms potato is produced on between ten and twenty fields and on four farms potatoes are planted on more than twenty different fields (Figure 4.7.).

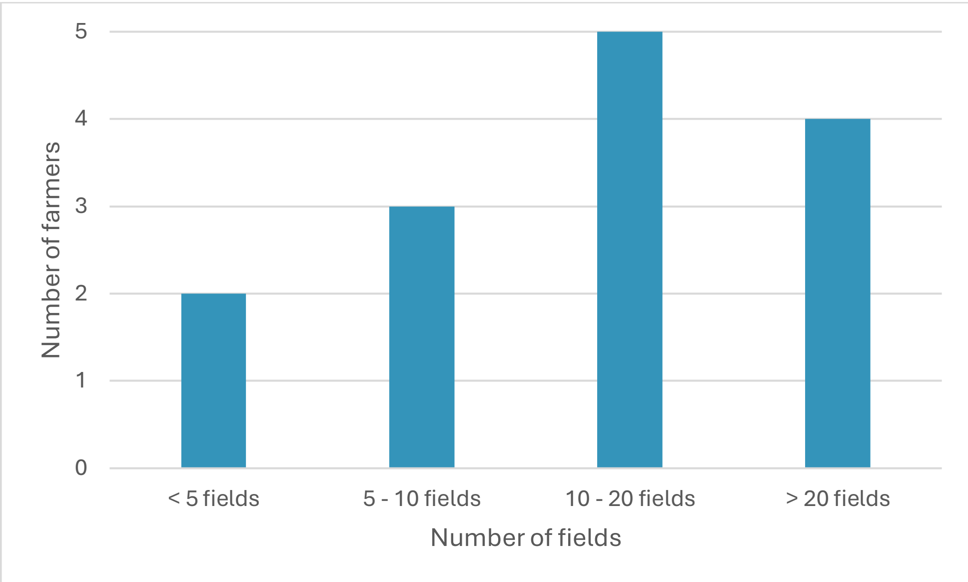

Figure 4.7. Number of potato tuber producing fields on each farm

The average distance between fields is on most farms between 4 – 5 km or less and on one farm is 10 km (Figure 4.8.).

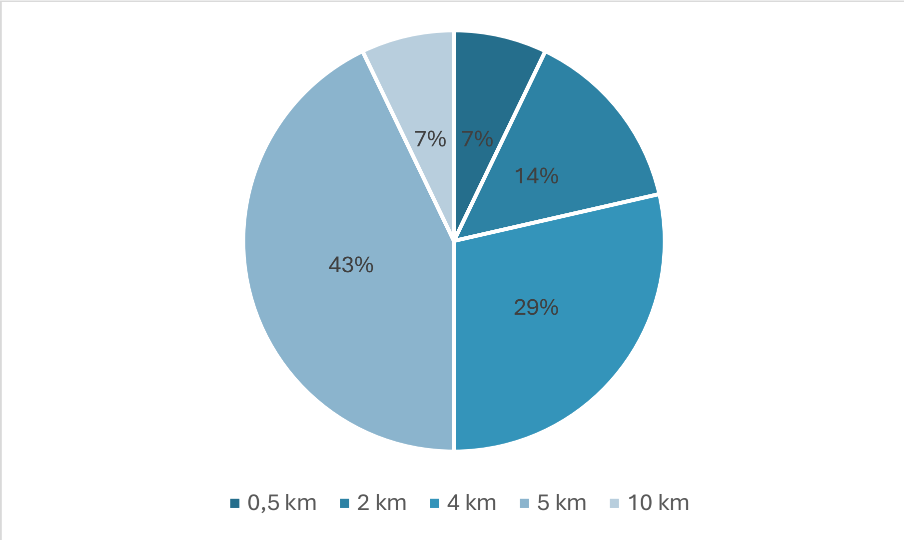

Figure 4.8. Average distance between fields on each farm shown in %

Big share of the farms - 9 respondents, have similar soil type between their potato fields; on 4 farms the soil type is different and only on 1 farm the soil types are very different between their potato fields.

In past three years (2021,2022 and 2023) the most frequently cropped potato varieties among responding farmers were Bellarosa, Camelia and Arizona (Figure 4.9.).

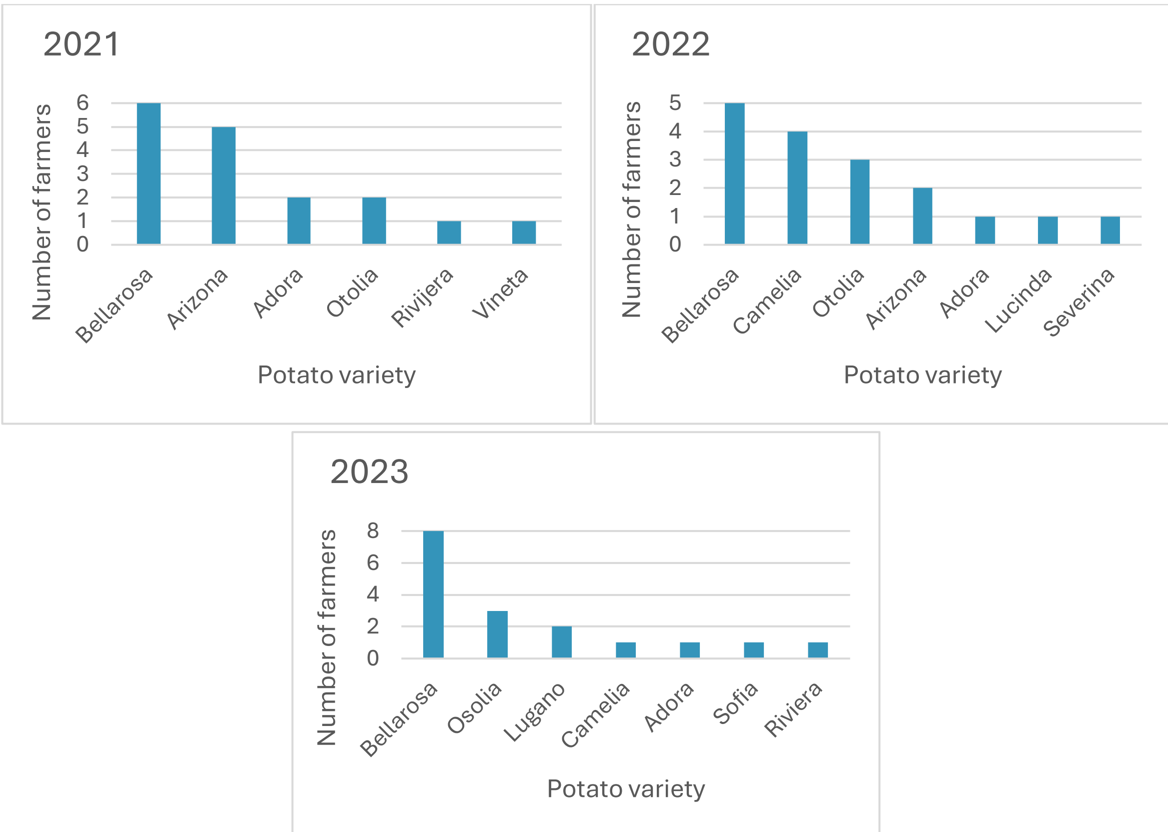

Figure 4.9. Most frequently cropped potato varieties in 2021, 2022, 2023

In the years 2021, 2022 and 2023, only 1 farmer did not plant potatoes on time according to the variety in years 2021 and 2023. Otherwise, everyone planted potatoes on time.

In years 2021, 2022 and 2023 all interviewed farms harvested potato on time according to chosen variety.

The average potato yields of our respondents varied from 21.43 t/ha in 2021, 23.06 t/ha in 2022 and to 29.13 t/ha in 2023 respectively (Figure 4.10.).

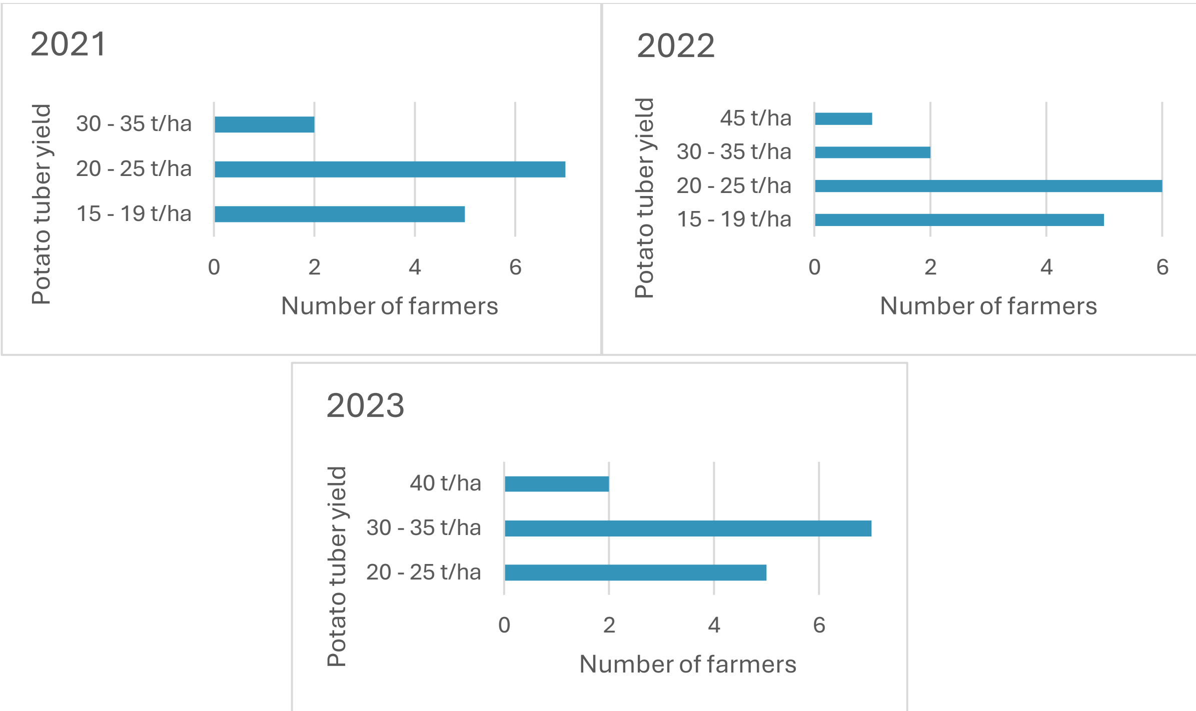

Figure 4.10. Potato tuber yields in 2021, 2022, 2023

All farmers are very well equipped with two or four rows' planters. Most of them have semiautomatic or automatic. In some cases, they have one row harvester.

In potato production among our respondents, mineral form of fertilizer is mostly used for fertilizing. Combined mineral fertilizers that contain a larger amount of phosphorous and potassium like NPK 5-11-21 or NPK 7-20-30 are used in combination with NPK 15-15-15 or in combination with mineral nitrogen fertilizer, KAN 27% N.

Only two farmers use manure to fertilize potato crops, one farmer uses organic fertilizer Stallatico pelleteto and none of our respondents uses compost for fertilization. Furthermore, five farmers use calcification before potato planting and one uses foliar fertilizer Agrimatco (Bioplex, AgroK, AMCOPOTATO, KELATEX Ca+B).

Farmers practice crop rotation differently (Figure 4.11). There is no farmer who grows potatoes every year. However, 6 farmers plant potatoes every second year in all fields, four farmers plant potatoes every third year and only two farmers plant potatoes every fourth year in all fields.

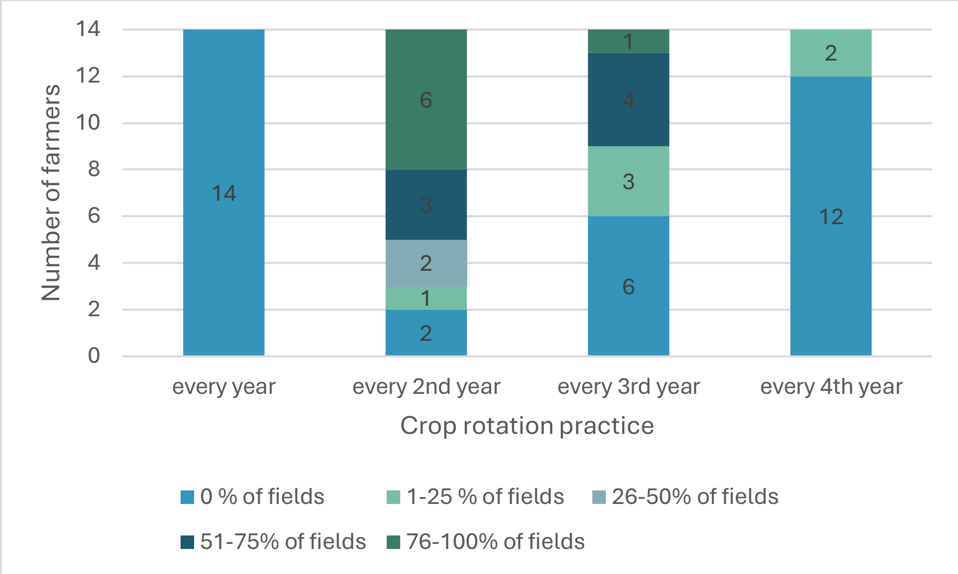

Figure 4.11. Crop rotation practices applied by farmers

The most frequently planted pre-crop are wheat (10) and maize (5), two farmers also use butternut squash and one respondent plants green manure as a pre-crop.

Corn (11) and wheat (6) are most often planted after crops, and two farmers grow triticale after potatoes.

None of the farmers uses irrigation in their potato production and question on the type of irrigation used, became irrelevant.

Farmers' answers to a group of questions related to knowledge and used practices of integrated pest management showed that all respondents were familiar with the concepts of integrated pest management (IPM). They also apply some integrated pest management practices.

To prevent and supress pests' appearance all farmers practice crop rotation and choice of resistant varieties, 13 farmers use certified seed material and practice harmonized fertilization, 12 farmers manage crop residues and 7 farmers practice intercropping. However, none of them practice conservation tillage nor flower strip growing (Figure 4.12.).

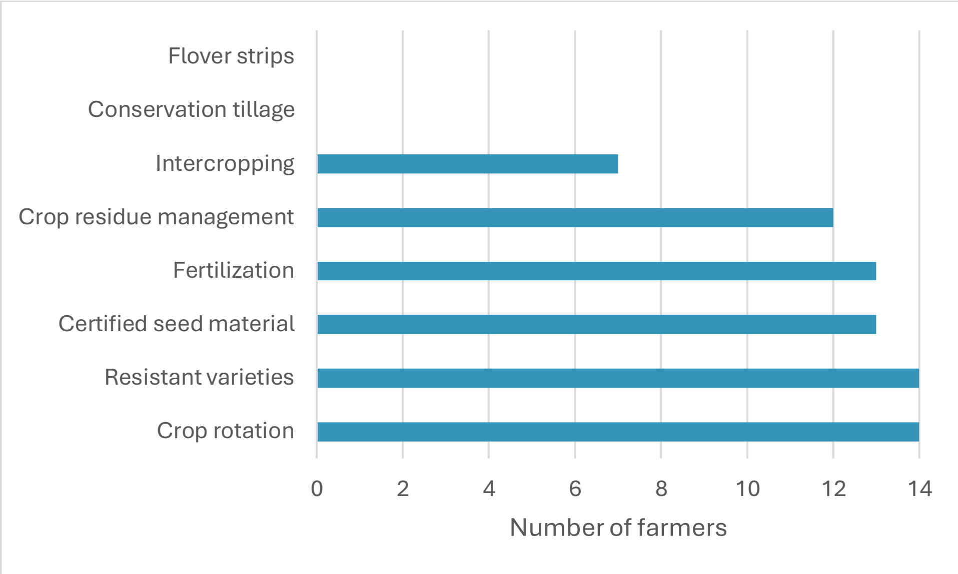

Figure 4.12. Number of farmers applying various measures to prevent and supress the pests

All farmers practice regular visual inspection of the fields and follow regional plant protection recommendations; three farmers use agrometeorological stations, and two farmers do the wireworm detecting soil survey. Nobody from the questioned farmers use traps to monitor pests (Figure 4.13.).

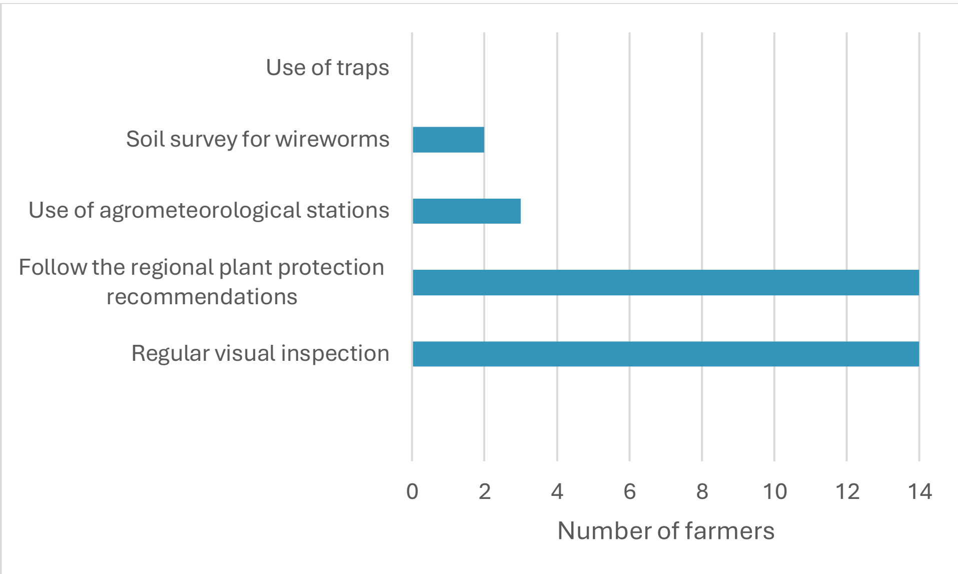

Figure 4.13. Number of farmers applying various measures to monitor occurrence of the pests

Thirteen farmers decide for chemical treatment based on both – the established infestation pressure and recommendation of Extension service; eight respondents decided for chemical treatment based on their experience and only one on contracting organization.

When it comes to the application of non-chemical methods to control pests almost all (13) apply mechanical methods as are collection of the pest and mechanical weed control. None of our respondents releases natural enemies nor applies biotechnical methods like mass trapping. Only 1 farmer practices cultivation, interrow precision weeding and uses microbiological insecticides and fungicides. One responding farmer does not use any of above-mentioned measures.

To determine the criteria for selecting chemical pesticides, we asked farmers to rank each of the four criteria according in four classes to importance: very important (4), important (3), little important (2) and unimportant (1) (Figure 4.14.). Efficacy is considered the most important criterion for the selection of chemical pesticides. The second most important criterion is toxicity to humans while the environmental impact on non-target insects is of minor importance and price plays no role. One of our respondents has stated, that an important factor when choosing chemical pesticide is the possible profit.

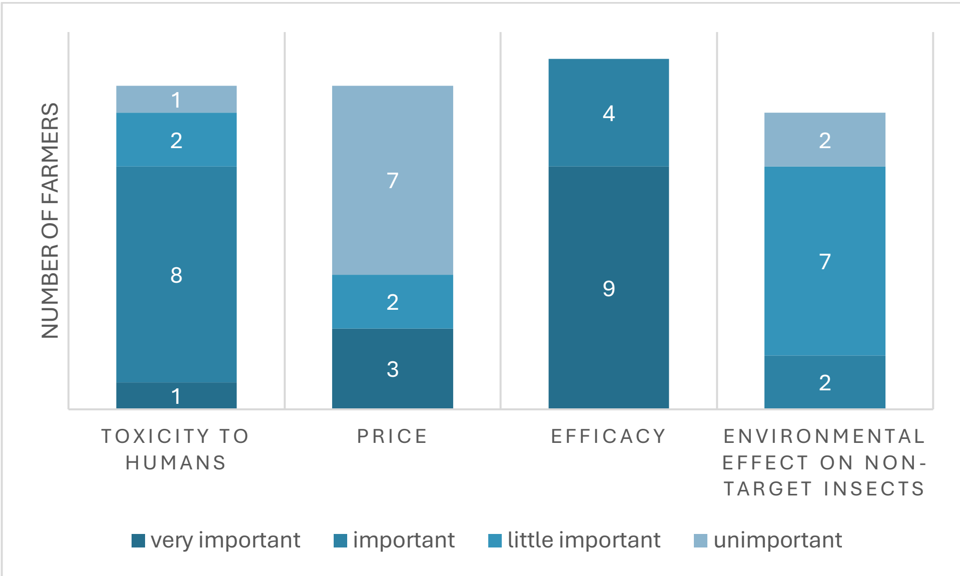

Figure 4.14. Criteria for selecting chemical pesticides according to their importance to farmers

All 14 responding farmers do practise the reduced pesticide use. Reducing pesticide doses is practiced by 3 respondents; 6 respondents reduce application frequency, and resorting to partial application of pesticide is practiced by majority of the respondents (11).

On all surveyed farms, anti-resistant strategies are applied (Figure 4.15.). All 14 respondents have stated that they combine pesticides with different modes of action and 13 respondents do monitor the resistance development. Furthermore, on 8 farms the application timing is being adjusted, but none of the responding subjects observes the occurrence of natural enemies to avoid pesticide application in case of high populations.

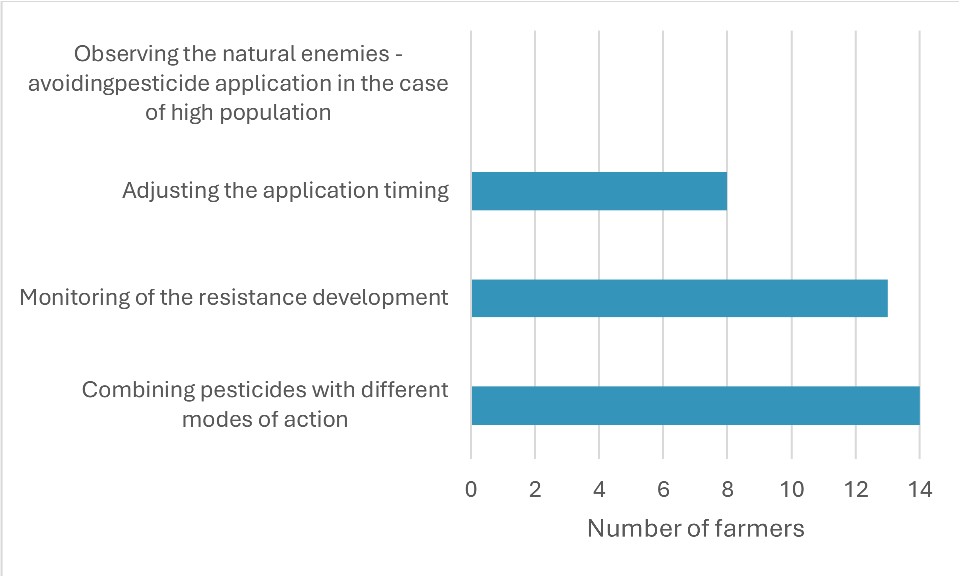

Figure 4.15. Numbers of farmers and anti-resistant strategies enhanced

All requested subjects do evaluate implemented measures (Figure 4.16.). The most common ways of evaluation are based on the yield quality and quantity (applied on 10 farms) and based on reached profit (applied on 9 farms). On 7 farms, the multi-year effect is observed (yield stability, pest population dynamic, changes in weed bank). None of the respondents evaluates implemented measures by the total absence of pests.

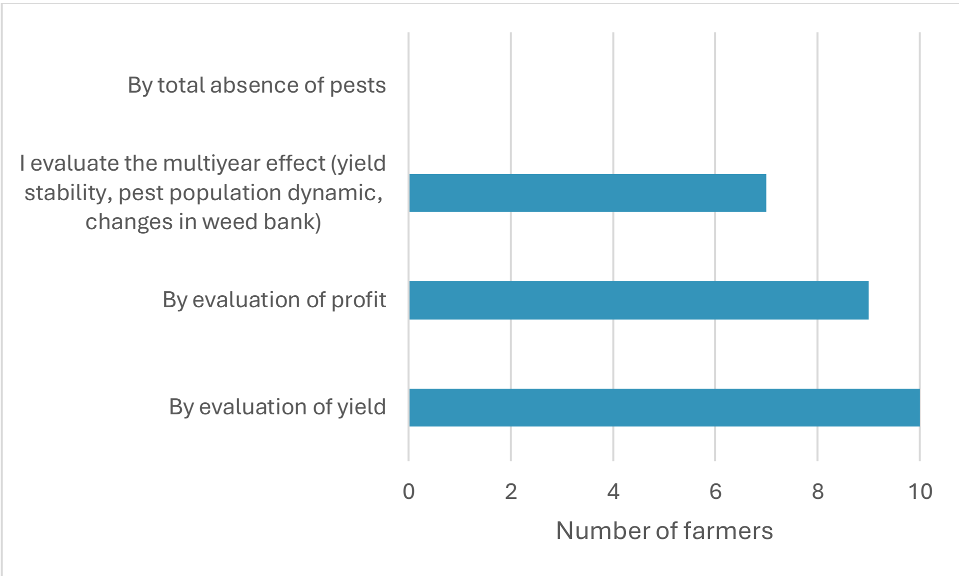

Figure 4.16. Approaches used to evaluate the soundness of implemented crop protection measures

Only 1 subject has stated an occasionally occurring problems caused by rodents. The rest of the respondents did not state any.

All 14 subjects have stated the Colorado Potato Beetle to be the most significant pest in their potato production. Wireworms have been stated as the second most significant pest by 2 respondents and 1 respondent states the Noctuidae to be a significant pest family.

Majority of respondents (13 farmers) has stated the late blight (*Phytophtora infestans*) to be the most significant disease. The second most common significant disease is the early blight (*Alternaria solani),* and it was stated by 11 respondents.

In the years 2021, 2022 and 2023 none of our responding subjects has used biological control nor biopesticides.

In the years 2021, 2022 and 2023 farmers have used the same chemical insecticides each year (Figure 4.17.). The most frequently used insecticides were chlorantraniliprole (14 respondents) and metaflumizone (13 respondents). Less frequently used insecticides were acetamiprid and deltamethrin, which were both used only by 1 respondent.

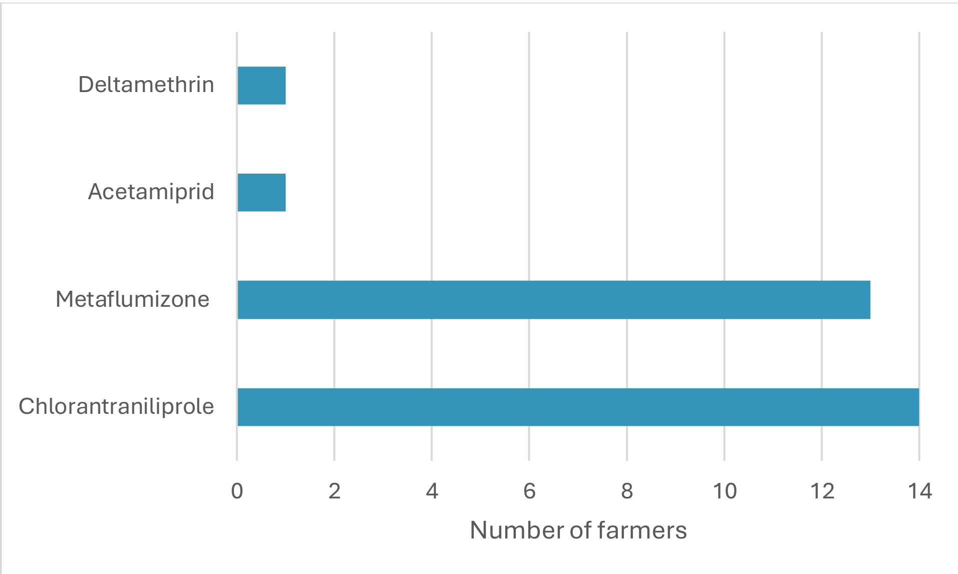

Figure 4.17. Chemical insecticides used in 20021, 2022, 2023

For chemical fungicidal treatment, the same substances were used in 2021, 2022 and 2023 (Figure 4.18.). The most used was mandipropamid, which was applied by 10 respondents. Next fungicides, dimethomorph + ametoctradin and fluazinam were applied by 9 respondents and difenoconazole was applied by 8 respondents. Cyazofamid has been applied by 7 respondents and propamocarb hydrochloride + cymoxanil was applied by 6 respondents. Least used fungicides were azoxystrobin, that was used by 2 respondents and fluazinam + dimethomorph, which was used only by 1 respondent.

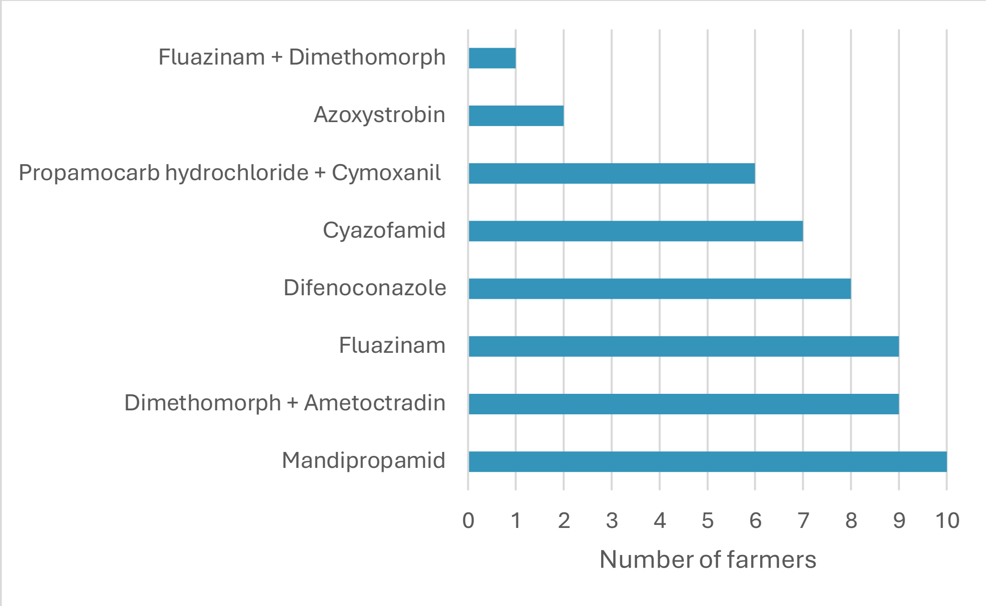

Figure 4.18. Chemical fungicides used in 2021, 2022, 2023

As the most common reason why farmers did not use biological control on their fields is lack of knowledge about this possibility (6 respondents) and the second most important is that they are not sure about the efficacy of biological control (5 respondents). Four of our respondents also stated, that they are not aware of where and how they could obtain it (Figure 4.19.).

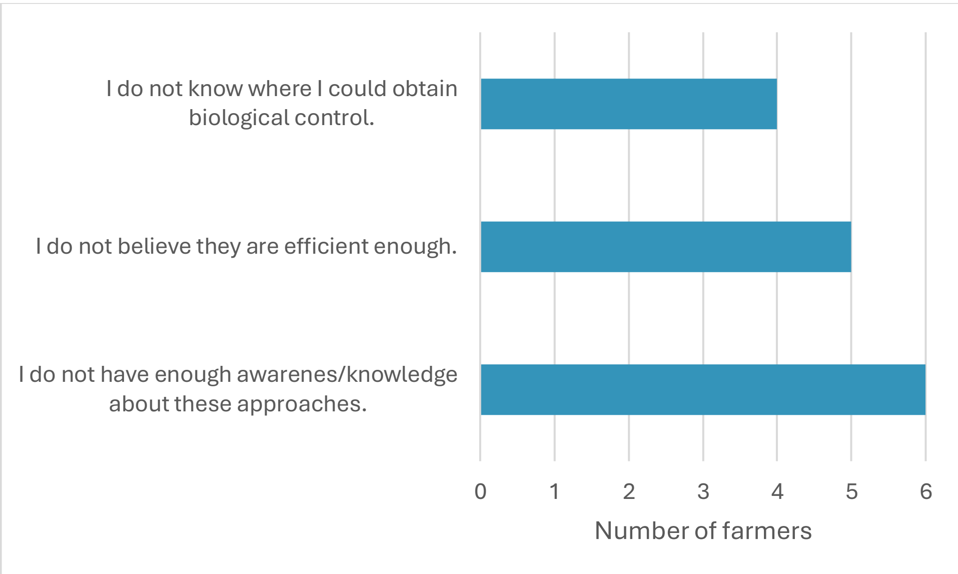

Figure 4.19. Reasoning for no application of natural enemies, microbial products etc.

Only on five of the surveyed farms, biodiversity is being supported in some way. At three farms, bushes are maintained; on one farm ecological infrastructure and green manuring take place; on one farm along with bushes, seminatural habitats are maintained and cover crops planted; on one farm, 5% of the fields is left to fallow every year.

12 responders have stated their greatest technical issues (Figure 4.20.). The most frequent issues are small sized fields (on 8 farms) and missing work force (on 7 farms). On five farms, farmers deal with technical difficulties connected to distance between fields, all these farms are dealing with small sized fields at the same time. On 2 responding farms, lack of irrigation belongs to greatest issues. On 1 farm, they are dealing with increased weeding issues due to lack of hummus and on 1 farm, one of the biggest issues connects to upcoming chemical pesticide ban and consequently its decreased availability.

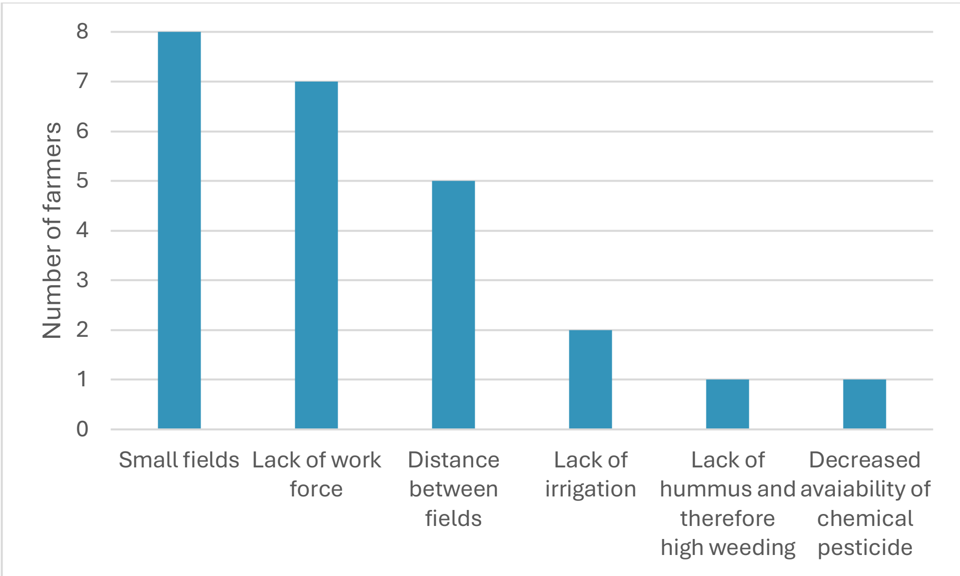

Figure 4.20. Greatest technical issues in potato production

The last question on the need to improve adaptation to the biological pest control was answered by all 14 farmers (Figure 4.21.). 50 % of the farmers, would be open to biological pest control if they had more knowledge or someone to guide them in the correct application of biological pest control. Four of the respondents need financial support and the necessary machinery to be able to use biological pest control. One respondent stated that the possibility of organized biological pest control on large areas would be necessary.

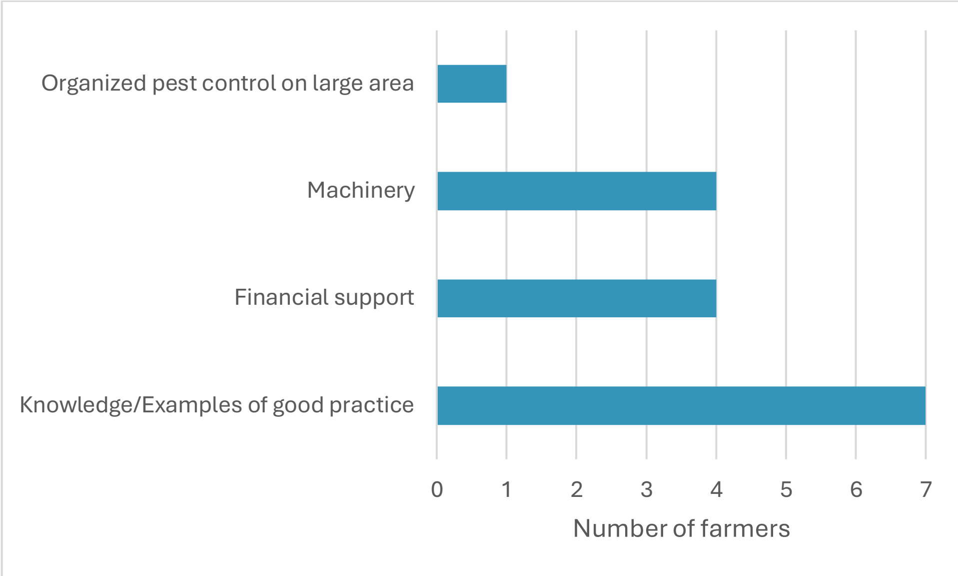

Figure 4.21. Factors that would help farmers to implement biological control

5. Discussion

The arable land area varies from 4 to 120 ha with the estimated average to be 37 ha while the potato producing area varies from 2,5 to 23 ha with estimated average to be 13 ha. According to Međimurska županija (2022), the overall arable area in Belica, where majority of questioned farmers is located, is 1 813 ha.

According to Eurostat (2022), nearly two-thirds of the farms in the EU were less than 5 hectares (ha) in size in 2020. According to European Commission (2017), an average size of EU farms is 14.4 ha, and the size of an average Croatian farm is significantly smaller 5.6 ha. At the same time, 50% of all Croatian farms are under 2 ha and almost 90% are below 10 ha. Based on this, we can classify the farms as large-scale sized farms in comparison to other Croatian farms and other EU countries.

Half of the questioned farmers produces potato on 50% or more of the overall arable land, the second half produces potato on 30% or less. Half of the farmers produces potatoes on between 20 and 23 ha, two farmers produce potatoes on less than 5 ha and the remaining five produce potatoes on between 5 and 12 ha. According to European Commission (2017), potato is in Croatia produced only in 1.4% from overall agricultural production (including livestock). Based on these results, we can classify our respondents as large-scale potato producers in Croatia.

The average potato yields of our respondents were 21.43 t/ha (2021), 23.06 t/ha (2022) and to 29.13 t/ha (2023). These yields are significantly higher than the average potato yields in Croatia in 2019, which was 15.20 t/ha (CEIC 2024). In comparison to available data on average yields in the Czech Republic (CZ) 28.15 t/ha (2021) and 28.67 t/ha (2022) (MZe, 2023), the yields were slightly lower.

Overall potato production in the EU in 2023, was 48.3 million tonnes. From this amount, the greatest share was produced in Germany (24%). The share of Croatian potato production was the same as Slovakian and Latvian (0.3%) (Europatat, 2024).

Majority of the farmers manages fields, that are partially owned and partially rented, only three farmers manage fully owned land. Farmers did not describe this as a major issue; however, it could have some effect on decision making for e.g. if to apply permanent measures (bush/tree planting around the fields; installation of irrigation systems etc.).

Greatest technical issues

Farmers have described, small fields and distance between fields as major technical issue. Despite the overall potato producing area sizes, only one of the farmers produces potatoes on less than 5 fields, four of the farmers even produce potatoes on more than twenty fields. The average distance between fields is in one case 10 km and in the other cases up to 4 – 5 km. Such conditions cause issues in technical practices and mechanical measures application (due to machinery size /type). Require proper time management when planning cultivation, harvest and any other agricultural measures and it makes it uneasy to perform needed measures on time on all fields. Due to spread location of fields, the use of engine is also increased.

Another common issue on questioned farms was the lack of work force. With increased work force it would be easier to implement or broaden already used technical and mechanical measures, to implement more principles of IPM.

IPM implementation

To prevent and supress pests' appearance, all questioned farmers have stated that they practice crop rotation. None of the potato producing fields are occupied every year, however on average, most of the potato producing fields are occupied every 2nd and 3rd year and most of the potato producing field are not occupied every 4th year. Hausvater & Doležal (2014a) state, that key prevention to avoid strong populations of CPB is crop rotation and recommend to crop potato on the same location only after 3 – 4 years break to interrupt its life cycle. Hausvater & Doležal (2014b) further state, that keeping such break in potato cropping also minimizes chances of soilborne late blight infestation as *P. infestans* spores do not last in soil that long.

Wheat and maize were the most frequently cropped as both pre-crops and after-crops. Potatoes were fertilized with manure only on two farms. According to Dvořák & Bicanová (2007), it is typical for potatoes to be planted after cereals, which do not leave many nutrients in the soil and therefore it is necessary to implement intercropping and green manuring. The best pre-crops for potato crop would be clover and alfalfa. After potato, the soil structure remains improved and rich in nutrients, if fertilized with manure and therefore it is a good pre crop for cereals and maize. It is recommended to improve current crop rotation with legumes, green manuring and manure fertilization.

All farmers have stated that they choose resistant varieties. According to Goffart et al. (2022), the two most important varieties for human consumption cropped in Northwestern Europe are Belana and Annabelle. Both these varieties are considered to be resistant varieties. Based on this data we can conclude that it is a common practice among European potato producers to crop resistant varieties.

Some of the varieties used by our interviewees do have a good resistance against late blight, however they are not resistant to the other pests that were said to be dealt with the most (CPB, early bight or wireworms). Their most chosen varieties and were Bellarosa – high resistance against viral diseases, mediate resistance against late blight and warts, Arizona – high yellow potato cyst nematode resistant and good late blight resistance, Camellia – highly resistant against late blight and viral diseases and Otolia – high wart resistance. Alyokhin (2009) states, that so far it has not been possible to breed a potato variety, resistant to CPB that would be available on the regular market. In 1995 the multinational American company Monsanto made an attempt to market the first genetically modified (GM) potato variety Russet Burbank, resistant to CPB. The insertion of Cry 3A-type BT genes provided resistance, and the variety was introduced to the market under the names New Leaf Potato, and New Leaf Plus (which was also resistant to viral infections). However, due to little interest from farmers, these GM varieties were withdrawn from the market (Opatrný 2012). Kadoić Balaško et al. (2020) further states, that up to this date, in the EU there are no CPB resistant potato varieties for human consumption on the market. According to Innovative farmers (2024), the Baby Lou and Melody show the highest resistance against wireworms from currently available varieties.

According to the obtained answers majority of the farms practiced harmonized fertilization, certified seed tubers are used, and crop residues are managed. Intercropping is practiced on half of the farms. On none of the farms, flower strips growing, nor conservation tillage are practiced. By introducing flower strips, biodiversity could be maintained – pollinators and natural enemies would be drawn to the fields, and it could positively increase yields and help reduce need for chemical pesticides.

On all farms, the regular visual inspections and following of the regional plant protection recommendations take place, but other forms of monitoring are not practiced much. On two farms the agrometeorological stations are observed and one soil survey for wireworm is done. On none of the farms, monitoring with the use of traps is used. Especially with the upcoming ban of chemical pesticides, monitoring and consequently chosen mechanical/ biological measures will be crucial in agriculture and incorporation of various monitoring methods (which are often inexpensive) is recommended. For instance, according to Morales-Rodriguez et al. (2017), pitfall and stocking traps filled with barley and wheat are highly efficient in wireworm trap-based monitoring.

Vast majority of our farmers base their decision on the established infestation pressure and on recommendations from the Extension service. Eight farmers decide based on experience and one on the decision of Contracting organization. Despite it is good to follow Extension service recommendations, it would be beneficial to broaden the monitoring tools use and evaluate the infestation pressure based on combinations of monitoring practices rather than just on visual inspections.

As for non-chemical pest control approaches, collection of the arthropod pests and mechanical weed control are practiced at most farms and at one interrow precision weeding and microbiological insecticides and fungicides are used. However biotechnological methods mass trapping and natural enemy release are not performed.

According to Göldel et al. (2020), pitfall pheromonal traps were introduced to control CPB in the early 2000s. Despite their efficacy drop after few days, a potential for their use of use has been observed. In laboratory trials, adult beetles treated with *Artemisia vulgaris* L. and *Satureja hortensis* L., have been recorded to produce higher numbers of sterile eggs. Among possible CPB natural enemies, that have been successfully tested in laboratory belongs for e.g. the Nearctic stink bug *Perillus bioculatus* (F.). However, this bug does not naturally occur in

Europe, and it is not yet known what effects could have its release on the environment and non-target organisms.

Pesticide use

It has been stated by the farmers that the possible CPB and late blight resistance development is being watched and chemical pesticides are used accordingly. The most frequently used insecticides were chlorantraniliprole (14) and metaflumizone (13). According to Kocourek et al. (2024), no chlorantraniliprole resistance or cross-resistance development has been described on CPB until today. According to Čačija et al. (2021), metaflumizon (along with spinosad) could be recommended in locations, where the CPB has developed resistance to other pesticides, however possible resistance development should be further monitored Less frequently used insecticides were acetamiprid and deltamethrin, which were both used only by 1 respondent. According to Kocourek et al. (2024), the CPB is likely to develop resistance to acetamiprid, based on observations that has been done throughout multiple regions in Czech Republic, where CPB resistance to acetamiprid have differed across the country. Dworzańska et al. (2023), has observed the CPB resistance development against deltamethrin.

The most frequently used fungicides were: mandipropamid (10), dimethomorph + ametoctradin and fluazinam (9) difenoconazole (8), cyazofamid (7) propamocarb hydrochloride + cymoxanil (6). Less frequently used fungicides were azoxystrobin (2) and fluazinam + dimethomorph (1). Abuley et al. (2023), states, that *Phytophthora infestans* has developed resistance against mandipropamid. According to FRAG-UK (2024), some dimethomorph and ametoctradin resistant late blight strains have been reported in the EU mainland. It has been observed that the efficacy of fluazinam has dropped and when used against the late blight, it has been providing inconsistent results over the past years (Schepers et al., 2018; Naim & Cohen, 2023). Articles on resistance development and difenoconazole have not been found and therefore it has been assumed that such cases are not known yet. Naim & Cohen (2023) further state, that cyazofamid provides excellent results in late blight control and no resistance have been observed so far. FRAG-UK (2024) further states, that no propamocarb hydrochloride and cymoxanil resistance development has been observed. Quin et al. (2016) states, that the development of azoxystrobin resistance in late blight is not very likely, contrariwise it seems, that with the global warming situation, the efficacy of azoxystrobin is increasing.

The use of chemical herbicides has not been recorded in this questioner, because mechanical control of weeds is easy to implement compared to other pests' mechanical management.

Our respondents have stated that efficacy is considered the most important criteria when selecting chemical pesticides. The choice of insecticides does align with this statement, however the choice of fungicides does not, as the late blight has already developed resistance to the frequently used fungicides. The second most important factor was toxicity to humans and the environmental impact on non-target insect were of minor importance. However, according to Pesticide Properties DataBase available online (https://sitem.herts.ac.uk/aeru/ppdb/en/index.htm), all used pesticides are highly or moderately toxic to both – humans and environment.

All farmers stated that they combine pesticides with different modes of action, based on information in Pesticide Properties DataBase, this is true for both – insecticides and fungicides. Majority of the farmers stated that they monitor the resistance development of pesticides, this is probably done by watching its efficacy in the fields. On more than half of the farms the pesticide application timing is being adjusted (with regards to the infestation pressure, weather conditions etc. but not to the occurrence of natural enemies in the fields).

Evaluation of the undertaken measures is based on the yield quality, quantity and reached profit. On half of the farms, the multi-year effect is observed. The evaluation is never based on the total absence of the pest.

Biological control use and limitations

Majority of the farmers did not use biological pest control, because they are not aware of the possibilities or lack knowledge on the topic. Less than a half does not believe that biological control would be efficient enough and some do not know where they could obtain such substances. Half of them is opened to biological pest control if they had an opportunity to gain more knowledge on the topic or could get a mentor who would guide them to correct measure applications. Smaller share of the farmers would need financial support and adequate machinery to implement biocontrol. One of the farmers was concerned about the possibilities for effective biocontrol on big scale areas. These results are a good starting point as farmers are opened to biocontrol use if they can obtain more information and an experienced guide.

Göldel et al. (2020) describes use of available microbial (*Bacillus thuringiensis var. tenebrionis (Btt)* and *Beauveria bassiana)* and botanical (neem extract, natural pyrethrin, and spinosad) as environmentally friendly insecticides against CPB. They are good examples of non-chemical control, that could protect the yields efficiently in combination with each other or lowered dose of chemical pesticides. Combinations of natural and chemical pesticides at lower doses can have various benefits a) decreased pollution (environmental) b) possibly slowed down resistance development (biological) c) cost per treatment is lowered (economical). In the future, the use of entomopathogenic nematodes against CPB could be also possible, with regards to successful laboratory experiments with *Steinerma feltiae* Filipjev, *Heterorhabditis bacteriophora* Poinar and *Steinernema carpocapsae* Weiser.

For wireworm monitoring, Kroschel et al. (2020) suggests soil sampling on each field and consequently an installation of bait and pheromonal traps. They further state, that naturally-ocuring entomopathogenic soil fungi *Metarhizium anisopliae* (also known as *M. brunneum*) is under research and seems to be successful in laboratory trials in wireworm biocontrol. According to Poggi et al. (2021), pot and laboratory trials with biocidal meals of *Brassica carinata* have been successful with the mortality reaching over 80%. This was confirmed by Catton et al. (2021) in Italy, during a successful on-field trials, when defatted seed meals of *B. carinata* controlled wireworms as effectively as chemical insecticides.

As for alternatives for chemical fungicides, there are not enough available non-chemical pesticides to control late blight effectively, currently only copper-based pesticides are available as a less toxic option. As for mechanical solutions, artificial termination of the potato crop vegetation before its natural death to avoid the infection spreading is recommended (Hausvater et al., 2021). On the other hand, the research shows, that alternative treatment of *A. solani* should be possible in close future. Da Silva et al. (2021), has proved that the early blight control with *Clonostachys* spp. isolates has been successful under greenhouse conditions. Treatment efficacy has ranged from 82% to 94% in the first trial and from 66% to 85% in the second trial. Field trials have not been done yet. Zhang et al. (2022) has proven that early blight control with secondary metabolites secreted by *Bacillus subtilis* were effective in limiting lesion development under the greenhouse conditions.

6. Conclusion

Based on results, obtained from Croatian potato producing farmers in the Međimurje county, using attached questioner, the sustainability of current systems has been evaluated.

1. Obtained results show, that farmers are already implementing well some IPM measures as are certified seed use, harmonized fertilization and crop residue management. However, some of the applied principles need to be improved for e.g. crop rotation diversity, better selection of chemical pesticide and broadening of monitoring methods. Some approaches need to be introduced, for instance establishment of flower strips and natural enemies' observation, fertilization with manure, conservation tillage and biological control use.
2. Despite implementation of some of the IPM principles, the most frequently appearing pests in Croatian potato crop fields (the Colorado potato beetle (*Leptinotarsa decemlineata* Say.), wireworms (*Agriotes* spp.)) and diseases (late blight (*Phytophtora infestans* deBary) and early blight (*Alternaria solani* Sorauer)), are treated exclusively with chemical pesticides, that are in most cases dangerous to human health and environment. These chemical pesticides are also losing efficacy over time, due to their overuse and resistant development.
3. The potato-based cropping systems in Croatia, as they are now, are not very sustainable and are dependent on regular chemical pesticide use. Considering the current approaches and chemical pesticide use, it can be difficult for farmers to stick with Farm to fork strategy already by 2030. IPM implementation must be improved, and biological control introduced.
4. Based on obtained results, farmers need more guidance and financial support to be able to reduce pesticide use while avoiding yield losses.
5. Most commonly, the farmers have not used biological control alternatives due to lack of knowledge on how such alternatives work and how to appropriately use them or obtain them. Another frequent reasoning was closely connected to lack of knowledge – the farmers are not sure if efficacy of such products would be high enough to protect their fields. On the other hand, it has been found that half of the farmers would be opened to switch to bio-based substances if they could obtain more information on this topic and an opportunity to discuss with an experienced mentor who would guide them step by step in the proper biological control use. Some of the farmers would need financial support to implement biological control.
6. These results show that if the EU commission wants the farmers to switch from chemical pesticides to biological control, one of the ways could be to offer farmers getting a qualification courses in biological control, in which they could study for themselves or could become a mentor on biological control in their region.

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8. Appendix

Evaluation of potato-based farming systems in Croatia, regarding their sustainability (environmental, production, economical) – Questioner

This questionary has been created to collect data that will be used as a foundation for practical part of a diploma thesis **Evaluation of potato-based farming systems, regarding their sustainability** with focus (not only) on sustainable plant protection. This diploma theses aims to observe and analyse the current level of sustainability in potato production and to suggest potential solutions that would be economically and environmentally friendly.

Your answers will be evaluated and compared to answers obtained by farmers from your region. The observed threads will be taken into an account and if possible, a sustainable solution will be suggested.

Please note that all the personal information you reveal in <u>PART A</u> will not be distributed to third parties, nor will be displayed publicly. In the outcome - Evaluation of potato-based farming systems diploma thesis, will be your data published anonymously under the mark FARMER 1, FARMER 2, etc.
Your personal data are collected only for the needs of authors, to be able to reach you back if needed.

PART A

Name and surname:
Farm name:
Farm address:
E-mail:

Part B

1. Farmland is:
a) rented b) owned c) combination: owned + rented

2. Management/structure:
a) Individual (family) farm / sole holder b) Partnership (several business partners manage the farm) c) Company (not partnership) with profit objective d) Company (not partnership) with non-profit objective e) Other; please specify:

3. Educational level of the farm manager:
a) university b) high school c) none

4. Experience of the manager of the farm in farming:
a) under 5 years b) 5-10years c) 10+ years

5. Arable land area of the farm *(all fields together in ha)*:

6. Potato production area *(the sizes of only potato producing fields added up):*

7. Production purpose of potato growing:
a) food - tuber potato b) seed

8. In addition to IPM principal farming, have you got any certification?
a) Organic (= BIO) b) Demeter (= biodynamic agriculture) c) None

9. Do you have commercial livestock at the farm? *(that could provide manure to be used as a fertilizer):*

10. Aside of potato production, does the farm also commercially produce other crops? *(vegetables, cereals, other arable crops etc.):*

11. How many fields are you producing potato on?
a) less than 5 b) 5-10 c) 10-20 d) more than 20

12. What is the average distance between the potato producing fields?

13. Soil type, between individual potato producing fields, is:
a) the same b) similar c) different d) very different

14. What is the major potato variety produced at your fields?
2021 - 2022 - 2023 -

15. Did you plant potato in optimal time? *(In past 3 years; according to the variety)*
2021 – 2022 – 2023 –

16. Did you harvest potato in optimal time? *(In past 3 years; according to the variety)*
2021 – 2022 – 2023 –

17. The potato yield in last three years *(the average of each variety separately)*:
2021: 2022: 2023:

18. Machinery: planter and harvester used – the prevalent type in your potato production:

19. Fertilizers used at your farm *(only in potato production)*:
a) Mineral – please specify which are used: b) Compost c) Manure d) Other; please specify:

20. How often do you plant potatoes on your fields - what ratio is occupied?
Every year: Every 2nd year: Every 3rd year: Every 4th year:

21. What crops are usually rotated with potato at your fields *(before and after):*
a) Before_____________________________________ b) After______________________________________-

22. Have you been irrigating your potato fields in last 3 years?
2021: 2022: 2023:

23. If you do use irrigation, what is the used type?
a) Drip irrigation b) Foliar irrigation

24. Are you familiar with the principles of integrated pest management (IPM)?
a) Yes b) No

If yes, please specify which IPM principles are brought to practice at your potato fields. Bellow you can find these practices divided into categories:

24.1. Prevention and suppression
a) Crop rotation
b) Certified seed material
c) Resistant varieties
d) Conservation tillage
e) Fertilization
f) Crop residue management
g) Intercropping
h) Flower strips
i) Other, please list____

24.2. Monitoring
a) Soil survey to determine the wireworm infestation level
b) Monitoring of one or more pests in the field by placing different types of traps
c) Regular visual inspection of the fields
d) Following regional plant protection recommendations and online pest and disease forecasting systems
e) Using agrometeorological stations
f) Others, please list____

24.3. Decision based on monitoring and thresholds
a) Deciding about the chemical intervention based on experience
b) Deciding on the chemical interventions based on the established infestation pressure
c) Deciding on the chemical intervention based on the recommendation given by Extension service
d) Others, please list____

24.4. Non-chemical methods
a) Applying mechanical methods – collection of the pests, mechanical weed control
b) Using microbiological insecticides and fungicides
c) Release of natural enemies
d) Applying biotechnical methods for pest control (mass trapping, confusion, sterile insect techniques)
e) Interrow precision weeding
f) Others, please list____

24.5. Pesticide selection – mark from 1-4 (1 = most important) the criteria for pesticide selection
__ Toxicity to humans
__ Price
__ Efficacy
__ Environmental effect to non-target organisms

__ Others, please list____

24.6 Reduced pesticide use
a) Reducing doses
b) Reducing application frequency
c) Resorting to partial application of pesticides
d) Others, please list____

24.7. Anti-resistant strategies
a) Combining pesticides with different modes of action
b) Adjusting the application timing
c) Observing the natural enemies – avoiding pesticide application in the case of high population
d) Monitoring of the resistance development
e) Others, please list____

24.8. Evaluation – how do you assess the soundness of the implemented crop protection measures
a) By evaluation of yield
b) By evaluation of profit
c) By total absence of pests
d) I evaluate the multiyear effect (yield stability, pest population dynamic, changes in weed bank)
e) Other criteria are important, please list them____

25. What are the most significant pests at your potato fields? *(please list them)*
Rodents - Insect - Diseases -

26. What pest control has been used on your potato fields in last 3 years. *Please write down exact names of used substances and against what pest they have been applied.*
Chemical pesticides: Biological pesticides/ Biological control:

27. If you have not used natural enemies, microbiological products etc., it was because:
a) I do not believe they are efficient enough. b) I do not have enough awareness/knowledge about these approaches. c) I do not know where I could obtain biological control. d) Other reason; please specify:

28. Do you support biodiversity at your farm? (bio-strips, ecological infrastructure, seminatural habitats, overwintering habitats, bushes, etc.). Please name examples from your current farming practice.

29. What are in general your biggest technical problems with potato production? Please specify them. How are you intending to approach them in 2024?

30. What would you need to increase the adoption use of the biological control (mechanics etc.) to reduce the chemical pesticides?

Biography

Marie Machačová was born in Brandýs nad Labem – Stará Boleslav, Czech Republic on August 25th, 1998. In 2018, she completed gymnasium in Prague with honours. During her gymnasium studies she took a gap year to study on a high school in Wales. In 2022 she graduated at Czech University of Life Sciences, Prague with a Bachelor of Organic agriculture. During her bachelor's studies she completed a 12-month long Erasmus+ exchange at University of Natural Resources and Life Sciences, Vienna. After her exchange she took part in Erasmus+ promotion and coordination at the university and became a head of faculty student organization called Pupen (the Bud). Throughout her life she took part in many beekeeping and beekeeping-related activities including promotion, international youth competitions and further education of youth and public. In 2022 she also completed specialized school in beekeeping. She applied for Danube Agrifood Master: Sustainability in Agriculture, Food Production and Food Technology in the Danube Region and has been chosen to attend the Hungarian University of Agriculture and Lifesciences, Gödöllő as her 1st year institution and University of Zagreb Faculty of Agriculture as her 2nd year institution. Marie is fluent in English and German and speaks a little Hungarian. In her free time, she likes to crochet, cook, swim and dance.