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Summary

The ban on the use of neonicotinoids means that prophylactic measures for beetroot crops need to be rethought. One possible lever is to increase the natural control of green aphids, which are the vectors of yellows, through appropriate landscape management. We have developed a spatially explicit model to explore the potential effects of deploying agroecological infrastructures, diversifying crop rotation or reducing plot size on the distribution of green aphids and the incidence of yellows in beet crops at landscape scale. Climatic conditions and pesticide treatments are taken into account, and the results of the first simulations are consistent with the expert knowledge used. Ultimately, the model will be used to explore the levels of aphid control by crop diversity and by their natural enemies at different scales (plot, farm, territory). The results will be used to discuss with stakeholders the conditions for deploying new management methods in agricultural areas.

Key words: Landscape diversification, Territorial management, Biological regulation, Modelling, *Myzus persicae*, Natural enemies, Beet yellows

Introduction

In the future, a global increase in temperatures and atmospheric CO2 concentrations is expected, which will have a major impact on agricultural production and could also favour crop pests in temperate regions, organisms that are particularly adapted to warmer conditions (Skendžić et al. 2021). It is estimated that a global average temperature rise of 2°C will lead to a yield loss due to insects of 19 to 31% on the main cereals (wheat, maize, rice; Deutsch et al. 2018). However, agriculture, which contributes to climate change while also suffering directly from it, must change its practices and, in particular, reduce its dependence on plant protection products, which means finding alternatives for managing pest populations.

The diversification of agricultural landscapes is a promising lever for controlling crop pest populations and thus helping to reduce the use of plant protection products in agriculture (Gurr et al. 2017). This diversification both increases the populations of pests' natural enemies, which will regulate them through predation and parasitism, and reduces the relative surface area occupied by the pest's host crop in time and space, reducing the resource favourable to them (Schellhorn et al. 2015). The establishment of semi-natural habitats, such as hedges, grassy or flowering strips or meadows, as well as reducing the size of plots and diversifying crops are known levers for promoting natural regulation (Vialatte, Tibi & Martinet 2023). It is therefore both the composition of the landscape and the spatial arrangement of crops and semi-natural habitats, i.e. its configuration, that have an impact on natural regulation (Estrada-Carmona et al. 2022, Martin et al. 2019). However, while the positive effect of landscape diversification is well recognised, its implementation as a management modality on a given territory is made difficult by the strong dependence on the ecological processes at play and the local context (Karp et al. 2018, Ratsimba et al. 2022). Indeed, the effects of the landscape interact with the ecological characteristics of pests and natural enemies (dispersal capacity, overwintering and feeding sites), the local cropping systems and climatic conditions. Furthermore, within a given plot, the effects of landscape structure can be strongly modulated by agricultural practices (Ricci et al. 2019, Petit et al. 2021). Implementing in situ experiments on a landscape scale to test the organisation of crops and semi-natural habitats is concretely difficult and is a medium- to long-term undertaking. Numerical modelling is an operational way of exploring and designing landscape management strategies for pest regulation, taking into account the specific biophysical and socio-technical features of a given landscape (Tixier et al. 2013).

In this article, we look at the particular case of the resurgence of beet yellows, which has been observed since the ban on the use of neonicotinoid treatments. This disease is caused by a complex of viruses belonging to different families with different modes of transmission, including poleroviruses. These viruses are transmitted by aphids, the main vector being Myzus persicae, the green peach aphid. Heavy outbreaks of these aphids, particularly in 2020, have led to temporary exemptions being granted for the use of neonicotinoids in 2021 and 2022. A national research and innovation plan (PNRI) is currently underway to define alternative operational solutions for reducing the incidence of beet yellows. As part of this plan, we are developing a spatially explicit model to simulate different scenarios for diversifying the landscape and agricultural practices on real landscapes in sugar beet production basins, in order to assess their potential impact on green peach aphid regulation, the spread of yellows and the yield losses associated with the disease. By exploring these scenarios, we should be able to identify and prioritise action levers that encourage biological regulation. The model is intended as an exploratory tool for dialogue between the various stakeholders (farmers, agricultural advisors, land managers, political decision-makers), with a view to devising solutions at landscape level. This tool will be used to identify research priorities and experimental systems to be tested on a landscape scale.

1. Model development

The model under development is a mechanistic and spatially explicit model that is being developed on the GAMA® modelling platform (Taillandier et al., 2018).

1.1 Assumptions

The model focuses on the aphid Myzus persicae, the main vector of yellows viruses. Although other aphids are vectors of these viruses, knowledge of virus acquisition and transmission by these aphid species is currently more limited. In this model we consider only poleroviruses, two of which cause beet yellows (BChV and BMYV). These poleroviruses have dominated infections in recent years. Finally, considering that winters in France are mild enough to allow aphids to survive without going through a sexual reproduction phase, we consider that population dynamics in year n+1 are initiated by individuals descended from populations present in the landscape in year n and having survived the winter, located on the oilseed rape plots. Thus, the aphid population in the spring is made up of descendants of populations that survived the winter locally, and aphids that colonise the landscape through the migration process. Finally, as little is known about the reservoirs from which the aphids acquire the viruses before transmitting them to the beet, they are not explicitly represented in the model. Viruses are introduced into the landscape by aphids colonising it in spring (through migration). Assuming that a constant proportion of these aphids carry viruses, they will inoculate the plants after landing.

1.2 Structure of the model

The structure of the model is shown in Figure 1. It represents the multi-year dynamics of green peach aphid populations within a landscape, taking into account weather conditions, aerial pesticide treatments, landscape composition and configuration, and the regulatory action of the aphid's natural enemies. The spread of the disease results from its transmission from aphids to beet during the growing season.

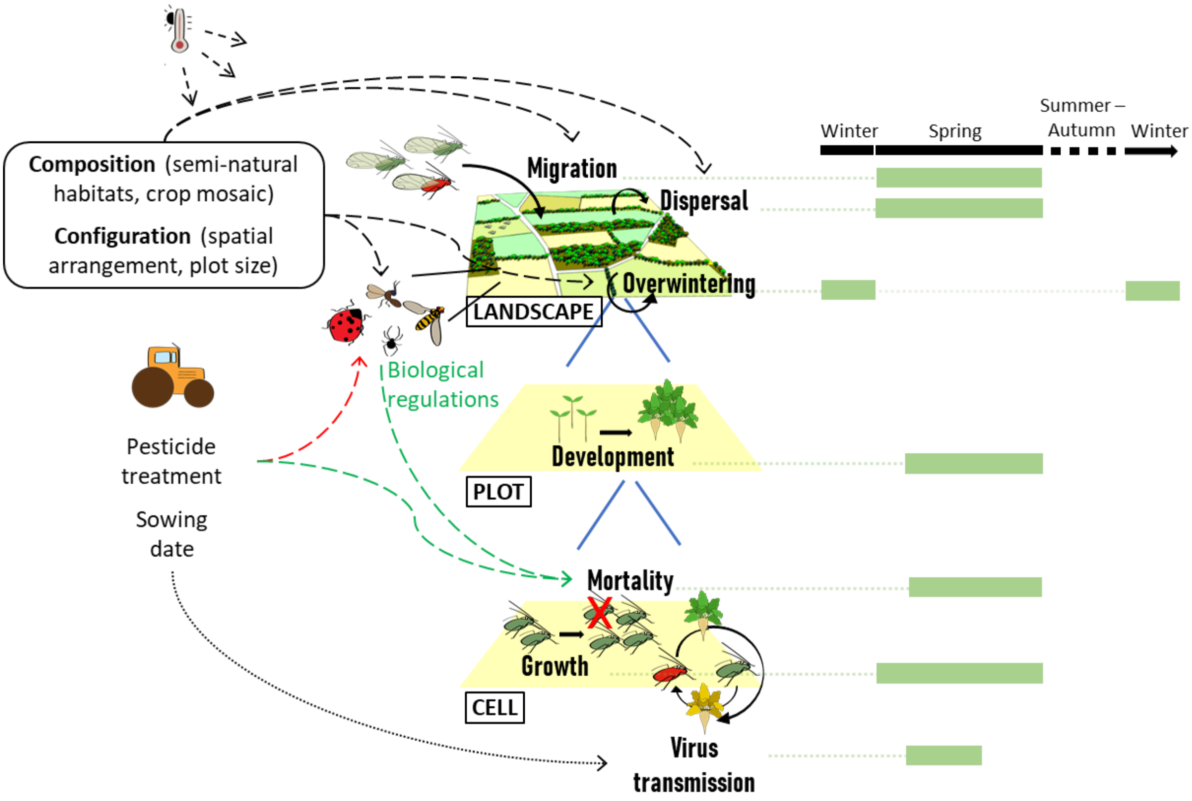

Figure 1. Main components of the dynamic simulation model of relationships between landscapes, agricultural practices, aphids, natural enemies and beet yellows. The model simulates aphid population dynamics (overwintering, migration, dispersal, growth, mortality), crop development, as well as certain agricultural practices (sowing, pesticide treatment) and the transmission of yellows viruses between aphids and plants (green peach aphids: healthy; red: viruliferous aphids; beetroot with yellow foliage: infected). The processes are represented at three different, nested scales (landscape, made up of plots, composed of one-hectare cells to which a land use is assigned). Landscape factors, farming practices and crop phenology have direct (dashed) or indirect (dotted) effects on aphid population dynamics and the transmission of yellows viruses. The seasonal period associated with each process is shown on the right of the figure. Temperature has a direct influence on all processes apart from predation and virus transmission at cell level.

1.3 Modelled processes

1.3.1 Spatial support

The model represents population dynamics on daily time steps, and real landscapes (e.g. 50 km²), discretised according to a grid made up of one-hectare cells. Data from the Registre Parcellaire Graphique (RPG) is used to assign a land cover to each cell, and the vegetation layer of the BDTOPO ® is used to spatialise semi-natural habitats, i.e. to assign an area of semi-natural habitat to each cell. The RPG can be used to spatialise crop sequences.

1.3.2 Crop phenology

Crop development is explicitly represented for the aphid host crops present in the landscape: beetroot, oilseed rape, potatoes, maize and grassland. The stage of development of the host plant influences various processes involved in the spread of the disease: the growth of aphid populations, their dispersal between plots (bare soils being unattractive to aphids) and the efficiency of virus transmission between aphid and beet.

1.3.3 Green peach aphid dynamics

Aphid population dynamics are explicitly represented from spring to early summer. Aphid populations are then reduced in proportion to the area of oilseed rape in the landscape in the autumn. During the winter, aphids overwinter locally on oilseed rape plots, and have a negative growth rate, which increases with low temperatures (Howling et al. 1994). The resumption of population growth in the spring is also dependent on temperatures,which influence its earliness. In spring, in addition to the pool of aphids overwintering locally, aphids also arrive from sources outside the landscape after travelling long distances by passive flight, carried by air masses (migration process). The daily abundance of this "aphid rain" is predicted as a function of winter climatic conditions and the regional composition of crops and semi-natural habitats (Luquet et al. in prep, PNRI SEPIM project; Fabre et al. 2021). Aphids surviving the winter, as well as aphids migrating from outside into the landscape, contribute to the growth of the local population in spring. This growth is modulated by temperature and the family and stage of development of the host plant (Whalon 1979, Williams 1995). Dispersal (local movement) of winged aphids between plots is triggered by the reduction in nutritional quality of the plant as its phenological development progresses (Müller et al. 2001). Finally, aphid mortality is due to pesticide treatments and the action of natural enemies. The effects of pesticide treatments are based on the effectiveness of Teppeki, recommended by the Institut Technique de la Betterave (ITB 2022), while also considering the lethal effects on natural enemies present in the plot. The treatment has the effect of reducing aphid populations in all the cells making up the treated plot by 75%, with an effect in the days following treatment on aphids landing on these same cells. The effects on natural enemies are parameterised taking into account both direct effects (lethality) and indirect effects (reduction in local resources), with a greater effect on aerial insects than crawling insects.

The population dynamics of natural enemies are not explicitly represented. The natural enemies considered in the model are archetypes (no specific species) known to predate or parasitise aphids: specialist enemies (parasitoids) and generalists (adult and larval ladybirds, spiders, ground beetles, hoverflies, lacewings and rove beetles). The formalism implemented is adapted from Jonsson et al. (2014), considering that the abundance of the different natural enemies is calculated as a function of the proportion in nearby host habitats within a radius varying according to the organism considered. For example, the abundance of spiders (ground dispersal) is favoured by the presence of semi-natural habitats at shorter distances than for ladybirds (flight dispersal). Aphid mortality due to natural enemies is then calculated as a function of the maximum attack rate of each enemy and their abundance, as well as aphid density. The lower the aphid density, the lower the number of aphids predated per enemy.

Table 1. Maximum attack rate of each natural enemy considered in the model. When the natural enemies are active, the mortality rate applied is calculated as a function of this maximum attack rate, the abundance of natural enemies and aphids on the cell.

Natural enemy		Maximum attack rate per capita (number of prey/day/natural enemy)	Reference
Parasitoids		20	Kumar *et al* (2019), Tahriri *et al* (2007)
Carabid beetles		20	Loughridge *et al* (1983)
Spiders	Lycosidae	1	Nyffeler *et al* (1988)
	Linyphiidae	15 / m² of web	Sunderland *et al* (1986)
Ladybirds	Adult	65	Omkar *et al* (2003), Xia *et al* (2003)
	Larva	80	
Hoverflies		33	Hopper *et al* (2011)
Rove beetles		10	Vickerman *et al* (1988)
Lacewings		13	Latham *et al* (2009)

1.3.4 Transmission of beet yellows viruses

Viruses are introduced into the landscape by the migration process, the "aphid rain" being made up of healthy aphids and aphids carrying viruses. The proportion of viruliferous aphids in the landscape in spring therefore depends on the abundance of aphids resulting from migration, and the abundance of aphids that have overwintered locally, all of which are healthy. Infected plants themselves become a source of infection for aphids after a latent period (6% of latent plants become infectious at each time step; E. Jacquot personal communication). The disease is spread between plots by viruliferous winged aphids (migration and dispersal processes), and between neighbouring plants by apterous aphids moving from plant to plant. The efficiency of transmission of poleroviruses from the aphid to the plant declines as the plant matures (up to the 12-leaf stage). The yield loss due to infection is represented considering that the later a plant is infected, the lower the associated yield loss, the maximum yield loss being set at 30% (ITB 2020) since only poleroviruses are taken into account.

2. Model behaviour tests

Exploratory simulations were carried out on a 49 km² landscape in the south of the Paris basin (7x7 km square) in order to explore and validate the consistency of the model's behaviour.

The actual landscape shown in Figure 2 contains 13.7% of semi-natural habitats, mainly woodland. Depending on the year, beetroot and oilseed rape each account for between 1% and 6% of the cultivated area. Two parameters were tested using a factorial design: the activity of natural enemies (active or inactive) and/or pesticide treatments (no treatment or 2 treatments maximum authorised).

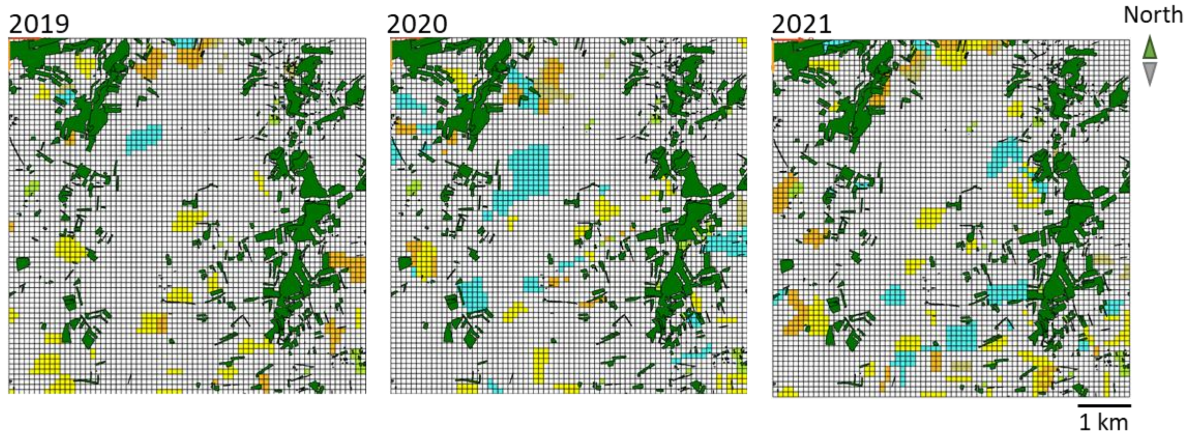

Figure 2. Simulated landscape over 3 years, at 1er May for the years 2019 to 2021. Semi-natural habitats are shown in dark green. Grid cells cultivated with a green aphid host crop are coloured (yellow: beetroot; blue: oilseed rape; orange: maize; beige: potato; light green: grassland).

Figure 3 shows examples of simulations carried out on this real landscape. As the model has not yet been calibrated and validated, the outputs presented below are intended solely to verify that the incidence rates obtained are indeed lower when natural enemies and/or pesticide treatments are activated, and that higher infection rates are obtained in 2020. Each graph corresponds to the output of a simulation, and shows the proportion of infected beet per plot.

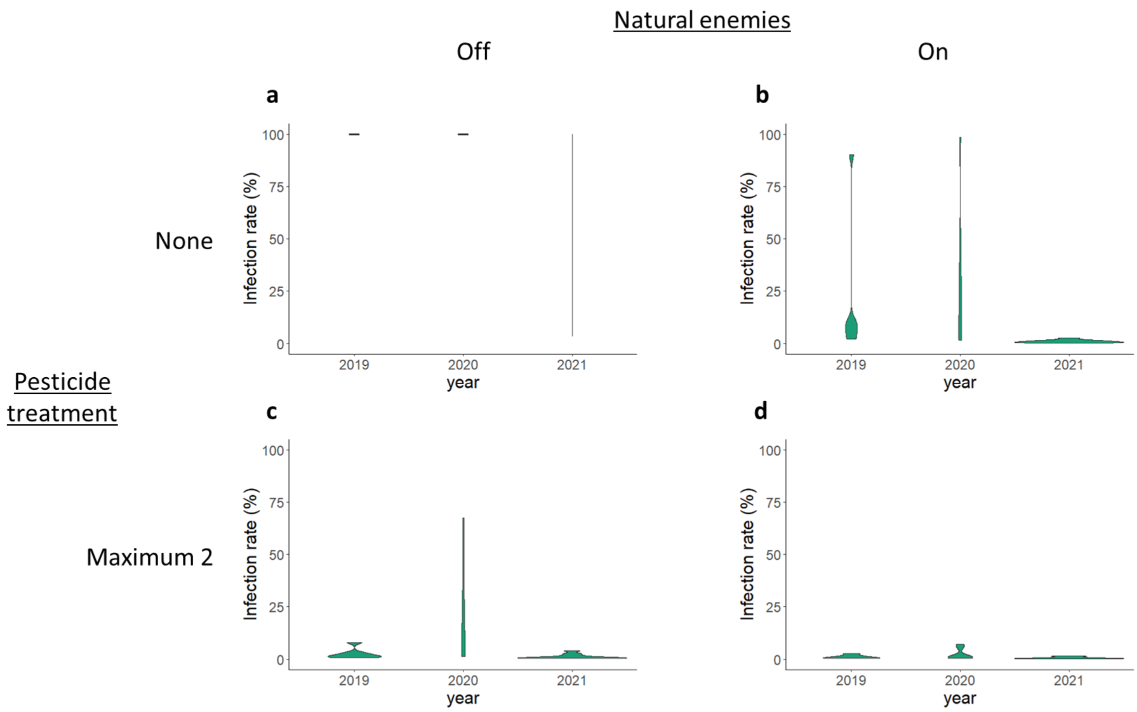

Figure 3: Distribution of average incidence of the disease per plot (proportion of infected plants, , based on an exploration of the model's behaviour before its calibration in relation to 2 parameters: the activity of natural enemies (activated or deactivated) and pesticide treatments (no treatment or maximum two treatments authorised).

The addition of natural enemy activity and the application of pesticides (Fig 3b, c, d) lead to much lower infection levels than in the situation without treatments and without natural enemy activity (Fig 3a). In addition, the infection rates obtained in 2020 are higher than in the other two years, which is consistent with what was observed in the fields.

The effectiveness of pesticide application is very high, but is not observed in reality. This can be explained by an optimised triggering of treatments (intervention for an aphid infestation threshold as recommended by the ITB) for all the plots in the landscape, which is not the case in real conditions where treatments are spread out over time. The preliminary results of tests on the effect of increasing the aphid presence threshold to trigger pesticide treatments show that these treatments are less effective in limiting the incidence of the disease.

These simulation outputs show that the model behaves consistently in relation to the expert knowledge used.

3. The next steps

3.1 Model sensitivity analyses

Several parameters of the model are uncertain due to the lack of knowledge, particularly concerning the biological characteristics of certain types of natural enemies (variable attack rates in the literature depending on the species, uncertainty as to the transposability of results obtained in the laboratory to the field, for example). We also transposed the knowledge available on other aphid species, such as cereal aphids, which have been studied more extensively than green peach aphids on sugar beet (e.g. predation rates). An analysis of the model's sensitivity to these hypotheses in terms of the outputs of interest (biological control effectiveness, levels of yellows infection and associated yield loss) will be carried out in order to assess the robustness of the conclusions to uncertainties over the parameters values. The most influential factors will be parameterised by calibrating the model on data from the Vigicultures© epidemiological monitoring network. The data used correspond to monitoring of the proportion of beet infested by aphids during the growing season, and the proportion of beet showing symptoms of yellows. Finally, the influence of the various factors taken into account in the model, in particular the composition and configuration of the landscape, will be estimated via a sensitivity analysis in order to identify the most promising management levers.

3.2 Testing landscape diversification scenarios

The model will be used to assess the effects of landscape management scenarios and farming practices on (1) the effectiveness of natural regulation, i.e. changes in aphid populations, (2) the spread of yellows (infected surfaces) and (3) yield losses associated with beet yellows. The scenarios tested will follow a gradient of importance of the changes made to the current agroecosystems: from the introduction of semi-natural habitats to changes in cropping systems (changes in rotations to diversify the crop mosaic and reduce the area under aphid-host crops, and/or changes in practices) and plot size. Different levers will be tested separately and in combination. Depending on territorial objectives and constraints, different combinations of levers, determined by the stakeholders, may be tested.

4. Expectations and outlook

The project will produce a number of results. Firstly, the synthesis of the knowledge required to develop the model has highlighted gaps in scientific knowledge, for example on the activity of natural enemies in beet production areas. The results of the analysis of the impact of the values of the parameters introduced into the model on the outputs of interest will enable us to formulate research priorities to refine our knowledge of these parameters and thus gain a better understanding of how biological control works in relation to the landscape and farming practices.

Then, the exploration of landscape management scenarios to reduce aphid pressure without resorting to insecticides will provide guidelines for experimentation on a landscape scale, both for the beet sector and the ITB and for other agricultural sectors also present in these areas.

The model could be enhanced to incorporate combinations of alternative solutions identified as part of the PNRI, such as sowing aphid-repellent companion plants in combination with attractive plants sown outside beet plots, or introducing varietal resistance mechanisms. In addition, work underway as part of the PNRI to gain a better understanding of the disease, in particular the identification of virus reservoirs during the winter and sources of infection, will provide key knowledge that can be incorporated into the model.

Lastly, the model could be used to support the design of very low pesticide or pesticide-free systems, with the scenarios serving as a basis for consultation on the introduction of landscape management methods that encourage biological regulation. The sensitivity analysis will provide key information on the weight of the various factors in the incidence of yellows at landscape level, thus guiding regional management priorities.

Ultimately, the model will be coupled with existing models representing the effects of landscape and cropping systems on the natural regulation of cereal aphids and oilseed rape pollen beetles. This will make it possible to explore effective management scenarios for controlling the various pests impacting crops grown in beet production areas.

Ethics

The authors declare that the experiments were carried out in compliance with the applicable national regulations.

Declaration on the availability of data and models

The data supporting the results presented in this article are available on request from the author of the article.

Declaration on Generative Artificial Intelligence and Artificial Intelligence Assisted Technologies in the Drafting Process.

The authors have used artificial intelligence-assisted technologies to translate from French to English.

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