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Economic Viability of companion plants in the Face of Virus Yellows in Sugar Beet

Martial Phélippé-Guinvarc'h and Jean Cordier

Abstract

Following the EU's decision to ban neonics in 2018, several alternative solutions have emerged from the dedicated French national research project initiated in 2020. Companion crops, such as barley or oats, sown at the same time as beet, have a repellent effect and reduce aphid numbers on sugar beet plants. This paper evaluates the economic viability of this particular solution and assesses how it reduces the risk of virus yellows infection on sugar beets. We show that although the companion plants may be effective in repelling aphids, the strict economic impact associated with the reduction of aphids population is mainly negative under cost-benefit assumptions currently adopted. Our analysis is based on the incidence model developed by Qi et al. It factors in the cost induced by the destruction of companion plants at a [4-6] leaf stage as well as a 'competition' effect between companion plants and beets. As a consequence of our analysis, we highlight the need to run further research work in two directions, (1) analyse the potential of additional benefits offered by the solution to complement its strict impact on the number of aphids in sugar beet fields and (2) analyse the potential benefits of synergies and combinaisons between this solution and other viable ones.

Introduction

Following the European Union's (EU) ¹ decision to ban neonics in 2018, and given the catastrophic sugar beet campaign witnessed in 2020, the French government has initiated - since January 2021 - a Program for Research and Innovation (PNRI). This program aims at exploring alternative solutions to neonics for the sugarbeet sector. One notable approach involves sowing (concurrently with sugarbeets) companion plants like barley and oats to repel aphids and therefore mitigate their impacts on sugar beets production (aphids being the main vector that spreads yellow viruses in sugar beet fields).

Jaworski et al. (2023) explain that intercropping refers to the simultaneous or relay cultivation of multiple crops during a growing season within the same field. This includes companion plants, strip cropping, and relay intercropping. As for crop diversification strategies, it may include trap cropping, agroforestry, and landscape diversification. They show that recent literature has addressed the benefits of crop diversification for arthropod pest control, examining essential ecological mechanisms, tools, and scales for implementing diverse cropping systems.

Sarkar et al. (2018) elucidate the functioning of companion plants in Figure 1. In their comprehensive literature review, the authors recognize that the development of an effective trap crop system is a costly process which often entails a secondary product with minimal market value. While biocontrol with natural enemies may offer favorable outcomes, reaching the desired results is typically a gradual and long-term process requiring much more time than the straightforward application of pesticides on trap crops (once pests have been trapped).

Our focus on companion plants is prompted by recent findings from 84 trials run by the French Technical Institute for Sugarbeet in collaboration with Agronomic Sugar Services from sugar companies as well as the participation of several agricultural college.

¹<https://food.ec.europa.eu>

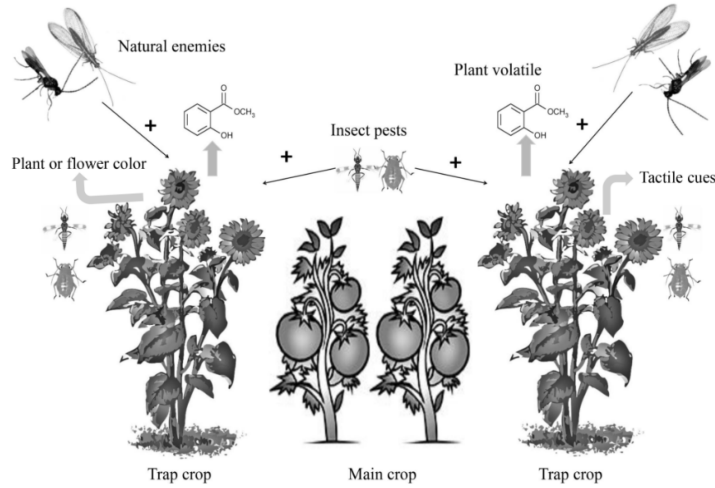


Figure 1: From Sarkar et al. (2018). ‘Role of trap crop to attract insect pests and natural enemies in a farming system.’

As elucidated by Fabarez et al. (2023) and by Fabarez (2023) (www.itbfr.org), various species have been evaluated since 2021: spring oats and barley showing the most promising results to reduce aphid population at this point.

This work has therefore paved the way for additional information regarding the feasibility and sustainability of implementing the ‘companion plant’ solution in an attempt to mitigate the economic risk associated with virus yellows infections in sugar beets. Based on trial results coming from the project mentioned above as well as economic results originating from the DEFT project run by the Association de Recherche Technique Betteravière (ARTB), and using previous papers from Phéllippé-Guinvarc’h and Cordier (2023), itself based on papers by Dewar and Qi (2021), by Qi et al. (2004), by Werker et al. (1998) and by Luquet et al. (2023) amongst others, a specific work has been performed on this solution.

While the efficiency of companion plants to repel aphids is acknowledged, our modelling work suggests that, based on current cost-benefit assumptions, there is hardly any economic incentive to use such solution to reduce aphid numbers. After defining the break-even point above which the beet loss are sufficiently big to make the use of companion plants economically useful, we show that the impact of a reduction in aphid numbers is not linear. Consequently, a 23% decrease in aphid numbers, as triggered by the companion plants, does not result in a 23% beet loss.

1 Two reasons for economic non-viability

1.1 Losses efficiency and costs

The primary effect studied for the companion plant is the reduction in aphid numbers. The benefit is related to the efficiency of the companion plant in managing this aphid population, particularly in terms of loss efficiency of virus yellows. The cost of implementing the companion plant is associated with its planting, its subsequent destruction to reduce competition between the two plants, and the estimated beet yield loss due to this competition. The net cost-benefit value BC_{PC} could then be written as :

$$BC_{PC} = (\ell - \ell_{CP}) - (C_{ICP} + C_{CCP})$$

where ℓ is the virus yellows loss without companion plant, ℓ_{CP} is the virus yellows loss with companion plant, C_{ICP} is the implementation/destruction cost, and C_{CCP} is the reduction in beet yield loss due to plants competition. Obviously, if there is no virus yellows loss, there is no companion plant benefit. BC_{PC} could be equivalently expressed in euros per hectare (ha) and as a percentage of the total expected beet revenue, assuming a beet yield of 80 tons per hectare together with a price of € 45/t beet, the total expected beet revenue is € 3600/ha. ARTB estimated that the average cost of sowing and destroying companion crops (C_{ICP}) is € 97/ha (or 2.7% of the expected beet revenue per ha).

As reported by Fabarez (2024), pilot trials at the farm have tested various solutions. Three crops: oats, spring barley and faba bean were tested as companion plants. Companion crops were tested with and without pesticides, paraffin oil, and *Lecanicillium muscarium*. Among the companion plants alone, oats showed the most promising results, especially when destroyed at the 6-leaf stage. This resulted in a 23% reduction in aphid numbers (noted ξ). In the meantime, the yield loss due to competition between the two plants was about 3% or € 108/ha (Figures 12 and 9 of Fabarez (2024)). Using a straight assumption (further discussed and challenged in the paper) that 23% fewer aphids means a 23% reduction in beet yield losses and considering that companion plants can lead to a 23% reduction in aphids population. It is then possible to compute minimum loss level that compensate the cost of implementing the companion plant measure, that we call the break-even loss. For $BC_{PC} = 0$ or $\ell - \ell_{CP} = C_{ICP} + C_{CCP}$ and total cost of $108 + 97 = 205$ €/ha, the break-even loss is 891 €/ha or 24.8% of the expected beet revenue per hectare (€ 205/ha equivalent to 5.7% of the expected beet revenue per ha divided by 23%).

Run with MPI climatic data - RCP 8.5 scenario, our model results shows that estimated beet losses never exceed the 24.8% break-even for the BMVY. In other words and under our cost-benefit assumptions, the companion plant has no positive economic impact when the plant is infected by BMVY.

The model also determined that the 24.8% break-even threshold can be reached for BYV with a 1.3% probability of occurrence over the period [2025-2100] (weighted by expected crop value).² Certainly, assuming a 23% reduction in winged aphids directly translates to a 23% reduction in losses is ambitious. However, our rationale holds if we can establish that the rate of loss reduction, based on the rate of aphid reduction, can be encapsulated by a linear function. Furthermore, this conclusion becomes even more valid if the rate of loss reduction is equal to or less than the rate of abundance reduction, as explained in the following sub-section.

1.2 The abundance reduction impact

1.2.1 Recall of some assumptions

This sub-section only recalls the elements of the article of Phélippé-Guinvarc'h and Cordier (2023) where the model of Werker et al. (1998) is the reference. The observed proportion of plants exhibiting symptoms of virus yellows infection (denoted as Y) increases over time and can be attributed to two sources of inoculum, namely primary infection (P) and secondary infection (S). This increase is a result of the interplay between the proportion of disease free plants ($1 - Y$) and these two sources of infection.

Considering that the total proportion of diseased plants is given by $Y = Y_p + Y_s$, the combined rate of change of the total proportion of diseased plants with respect to time is given by

$$dY/dt = (r_p P + r_s Y)(1 - Y)$$

The primary inoculum, represented by the variable P , is defined as the number of migrant viruliferous aphids that lands on beets and feeds on it. The determination of P is based on the total number of aphids migrating in spring, which is assessed using suction traps from the Rothamsted Insect Survey. The relationship between P and N , the total number of migrating aphids in spring, is set by the equation:

$$P = 1 - e^{-pN} \tag{1}$$

This equation corresponds to the multiple infection transformation and involves the constant of proportionality denoted as p . The use of this transformation is necessary to stabilize the values of P since the number of migrating aphids (N) exhibits significant variations from one year to another.

² Considering all oat trials, the efficacy reached 36% reduction in aphids, but with an average yield loss of over 9% (Figures 2 and 9 of Fabarez (2024)), the break-even loss would be € 421/ha (€ 324+97/ha or 11.7% of the expected beet revenue per ha) divided by 36%, equivalent to EUR 1169/ha (or 32.48% of the expected beet revenue per ha). If we combine the results, assuming that in the future we can optimize the use of the companion plant to achieve maximum effectiveness of 36% and a minimal loss due to competition of 3%, the break-even of loss to reach may be 15.82%. The probability of 15.82%<BYV loss occurring reaches 10.8%.

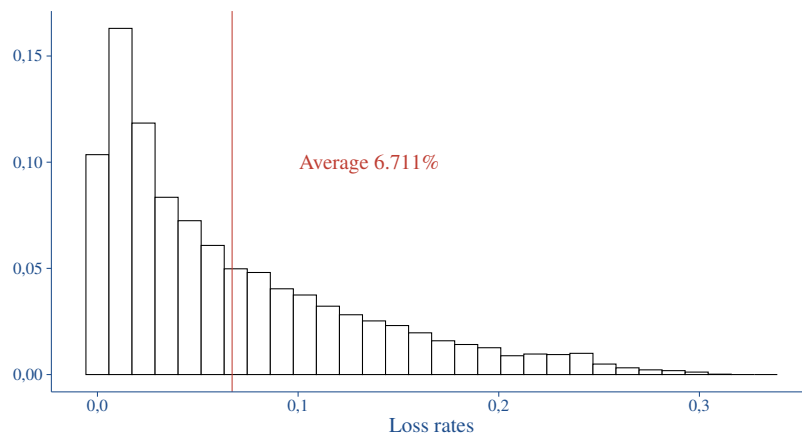
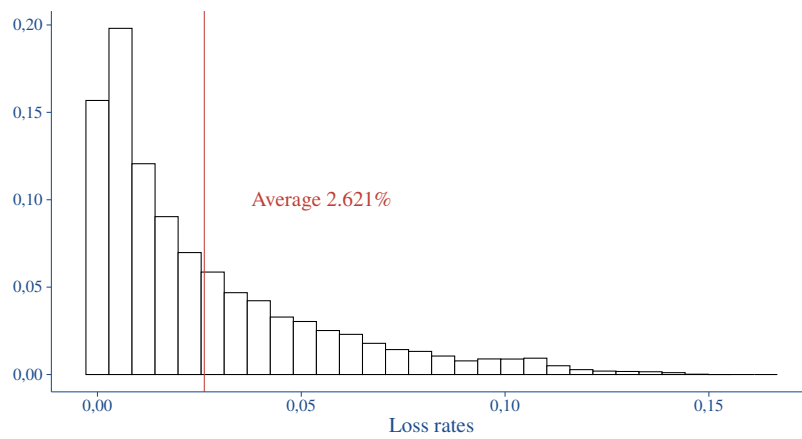


Figure 2: BMYV (top) and BYV (bottom) Density Loss 2025-2100 (weighted by expected crop value).

In this investigation the infection cycle is initiated at time t_0 , then $Y_0 = 0$ and the solution is:

$$Y = \frac{1 - e^{-(r_p P + r_s)(t-t_0)}}{1 + \frac{r_s}{r_p P} e^{-(r_p P + r_s)(t-t_0)}} \quad (2)$$

Time t_0 coincides with the start of the migration of the aphids *Myzus persicae* in spring, and at this point, the proportion of infected plants, denoted as Y_0 , is set to be zero.

Last but not least, loss depends on the phenological stage when inoculated and on virus. The more mature the plant, the more resistant it becomes and the lower the losses. Furthermore, as highlighted in Figure 3, in the case of early infection, a plant infected by BMYV suffers a loss of about 30%, whereas in the case of BYV the loss is close to 50%. As a consequence, the whole beet field is not contaminated the same way and losses may differ from one place to another within the field even if it is eventually infected and present similar yellow leaf symptoms.

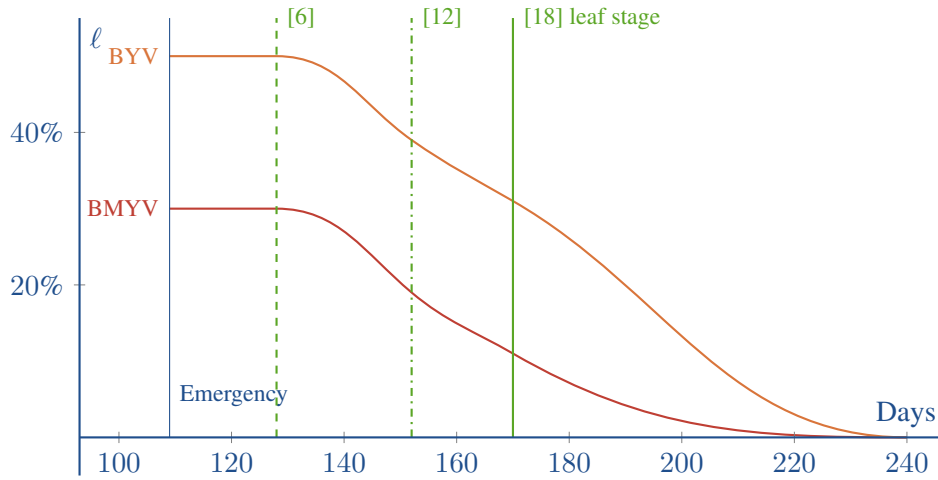


Figure 3: The expected beet yield loss ℓ due to BMYV (dark orange) or BYV (orange) infection relative to this phenological stage. In this figure, the days are chosen to correspond to the average day of the 2025-2100 emergency stage (blue), [6], [12] and [18] leaf stage (green).

1.2.2 Abundance and first aphid flights impacts on incidence and losses

The equation 2 shows that incidence is a nonlinear function of abundance and first aphid flights. In addition, while the number of new infections increases, the rate of loss decreases as the plant matures and becomes more resistant. It is difficult to understand how a 23% aphid's number reduction in the beginning translates into a beet yield loss in the end. The aim of this section is to clarify the relationship between the reduction in aphid numbers and the reduction in losses. In the following plots, phenological stage days are based on average days in the campaign for the future years 2025-2100. As recommended by ARTB (Phélicpé-Guinvarc'h and Cordier, 2023), the assumption of Qi for the northern region is the most appropriate in the French context and was then used in the graph.

The figure shows the relationship between loss and abundance with and without companion plants. The plot on the left shows that the loss increases with the number of aphids, and that the reduction in aphid numbers due to the companion plant (dotted line) also reduces the loss. The plot on the right shows the effectiveness of the companion plant. What's most remarkable is that the reduction in incidence at the 6-leaf stage is stable regardless of abundance, while abundance increases as the crop progresses. Thus, although a decrease of 23% in aphid abundance has an effect on beet yield loss close to 23% when abundance is close to 0, this effect decreases asymptotically to 0 at high abundances. In other words, the greater the loss due to aphid abundance, the less effective the companion plant.

If we carry out the same exercise on the first aphid flight in Figure 5. Only day values between 109 and 128 have been plotted. Even if the first aphid flight occurs earlier, they cannot land on the beet, and

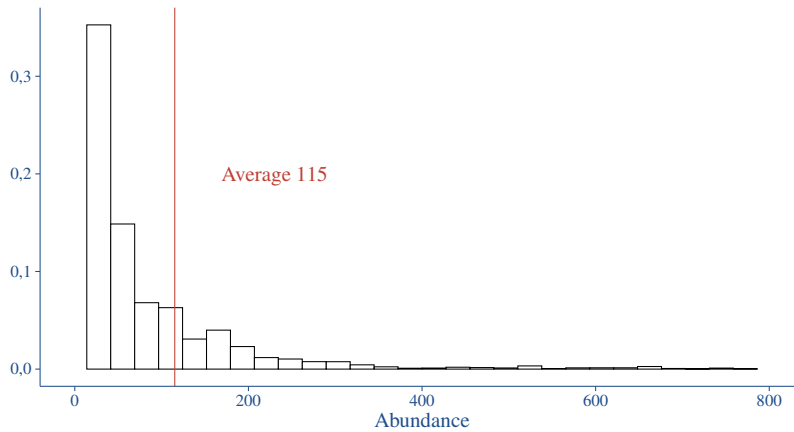


Figure 4: Abundance density 2025-2100 (weighted by expected crop value and where Abundance < 800)

after the [6] leaf stage, the companion plant could be destroyed before the first aphid flight. The plot on the left shows that the loss increases when the first aphid flight is earlier and the one on the right shows that the companion plant is less effective when the first aphid flight is earlier. The conclusion is the same, the greater the loss due to early aphid flights, the less effective the companion plant.

For the entire MPI scenario (IPCC 8.5), we calculate the loss with companion plant ℓ_{CP} for BYV virus using abundance and stage days provided by the model, as detailed in Phélippé-Guinvarc’h and Cordier (2023) (450450 scenarios = 429 Agricultural Regions \times 7 planting dates \times 150 years). The probability of $\ell_{CP} < \ell$ occurring is equal to 0.

2 Discussion

Our cost-benefit analysis of companion plants as a solution to contain the economic risk of virus yellows infections on sugar beets is largely negative under assumptions currently adopted and generally accepted. No circumstances of infection may justify to use companion plants and result in a positive economic result as opposed to not doing anything. We found that the use of companion plants is too costly (5.7% of income per hectare) with respect to expected virus yellow loss (2.621% for BMV and 6.711% for BYV) and to efficiency (23%). In addition, we have shown that significant losses occur when aphids are abundant and land early, when estimated efficiency is lowest, because the effect of aphid reduction on beet yield loss is non-linear.

Of course these results are conditional to the quality of the Qi model and to the quality of the cost-benefit assumptions that have been used. As for the Qi model, its use as a reference for many projects of the French national research program surely calls for its use by the GREcoS project although some theoretical aspects of it may be questionable. Regarding the estimation of the full cost to use companion plants, it has been set to an optimal level as we considered only a 3% beet yield losses due to competition between plants, the reality in the fields being slightly higher than that.

It is also worth noting that our results are in line with previous studies. In particular, Chauvin and Soubeyrand (2022) used machine learning to identify risk factors for virus yellows in sugar beet. It was surprising to find that the presence of aphids was only the 11th most significant factor (out of 154). The authors argue that since winter severity variables are excellent predictors of aphid’s abundance, the role of the abundance variable is overshadowed by other factors in the statistical analysis. Although this argument is relevant, our analysis also highlights that the non-linear relationship between abundance, first aphid flight time and losses may also explain Chauvin and Soubeyrand’s findings.

There is one notable aspect of work of Fabarez: the variability in performance. This is also the case for other alternatives to neonics proposed by Laurent et al.. Paradoxically, the variability in companion plant efficiency could have allowed us to identify certain cases where the reduction in beet yield loss due to the companion plant was better than average. Of course, the existing variability would also include

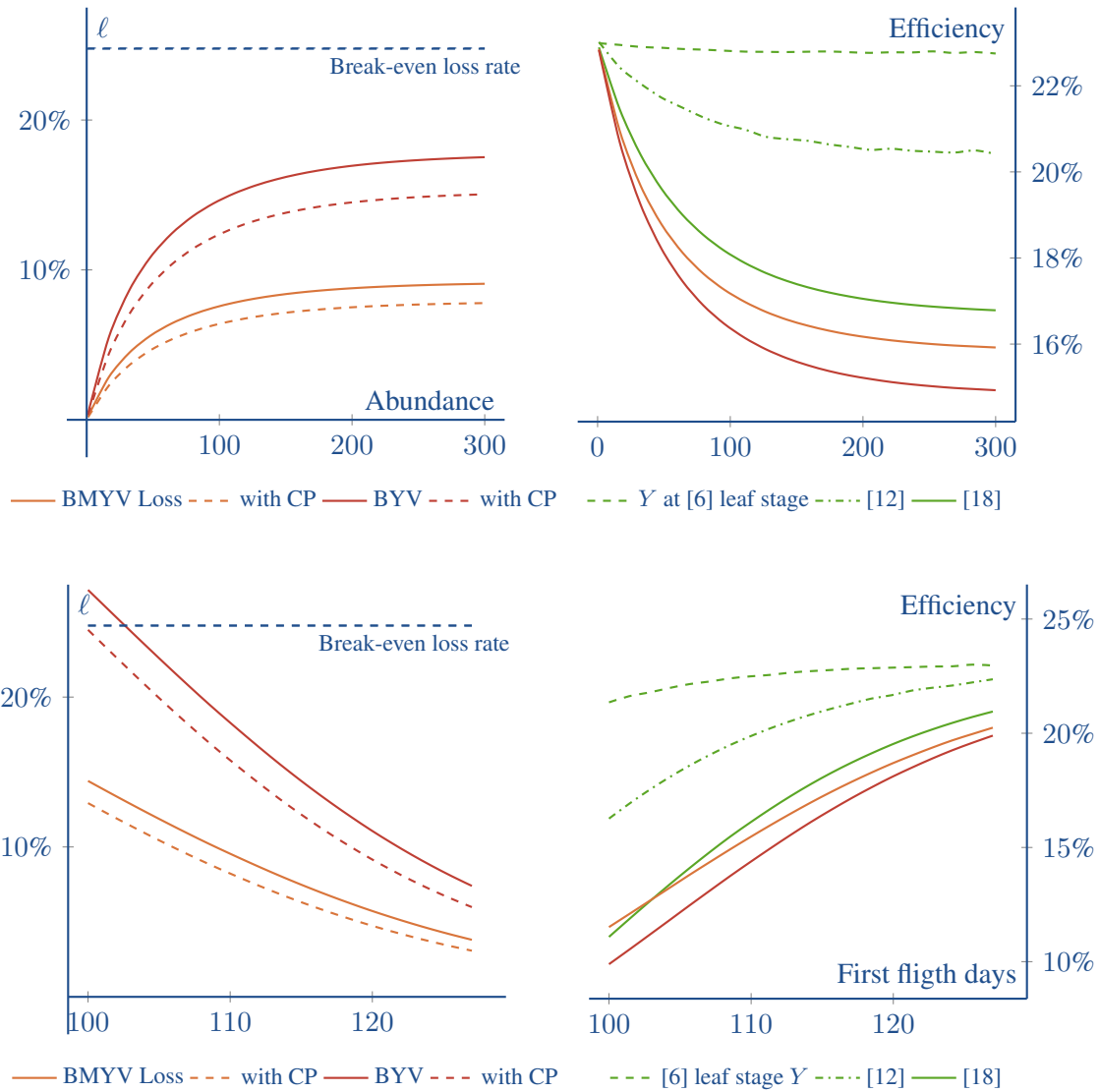


Figure 5: **At the top :** the effect of abundance on the loss ℓ and the incidence Y . Left, the figure shows the loss that depends on abundance without (lined) and with (dashed) companion plants. On the right, the efficiency of reducing incidence (green) and losses (oranges) is shown.

At the bottom: the effect of first aphid's flight day on the loss ℓ and the incidence Y . Left, the figure shows the loss that depends on first aphid's flight day without (lined) and with (dashed) companion plants. On the right, the efficiency of reducing incidence (green) and losses (oranges) is shown.

cases where this solution is less efficient than average. Integrating this variability would therefore mean adding a risk premium to the full cost of the measure, thus increasing the break-even loss level of the companion plant measure.

Companion plants may be considered in synergy with other solutions, for instance using repulsive odor measures. A synergy between two solutions could reduce implementation costs, multiply efficiency, or generate significant externalities, such as soil enrichment and increased plant resistance to other risk factors. All consulted literature emphasizes the need to combine technical solutions in an effort to tackle the development of beet yellows. However Fabarez admit: ‘It has been difficult to select and massively deploy trials that combine multiple levers (or solutions) because of the lack of effectiveness of the levers alone.’ At this point, these solutions have not shown tangible economic benefits (see for example Francis et al. (2022), Sarkar et al. (2018), Jaworski et al. (2023)).

Conclusions

The originality of the article lies in the provision of a cost-benefit analysis based on modelling and quantification. The use of companion plants is almost never a viable economic solution within the framework of our cost-benefit assumptions and given its efficiency in reducing aphid numbers. Our modeling work calls for further simulations using other technical or combined solutions. These could more significantly reduce the number of aphids landing on sugar beets and transmitting beet yellows virus, or have other effects such as reducing implementation costs or providing other valuable externalities.

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2.2 Funding

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