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Economic Viability of companion plants to lower the spread of Virus Yellows in Sugar Beets

Martial Phélippé-Guinvarc'h and Jean Cordier

Abstract

Following EU's decision to ban neonics in 2018, several alternative solutions have emerged from the dedicated French national research program initiated in 2020. Companion plants, such as barley or oats, sown at the same time as beets, proved to have a repellent effect and reduce aphids' presence in sugar beet fields. This paper evaluates the economic viability of this particular solution and assesses how it reduces the risk of sugar beet infections by virus yellows. We show that although 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 costs induced by the planting and destruction of companion plants at a [4-6] leaf stage and factors in 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 potential benefits offered by synergies and combinations of companion plants with other viable solutions used to mitigate the spread of virus yellows in sugar beets.

Introduction

Following 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 implemented - 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 in order to repel aphids and therefore mitigate their impacts on sugar beet 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.

As illustrated in Figure 1, Sarkar et al. (2018) elucidate the functioning of companion plants. In their comprehensive literature review, authors recognize that the development of an effective trap crop system is a costly process which often entails a secondary product but often with minimal market value. While biocontrol and natural repelling solutions may offer favourable 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 colleges.

¹<https://food.ec.europa.eu>

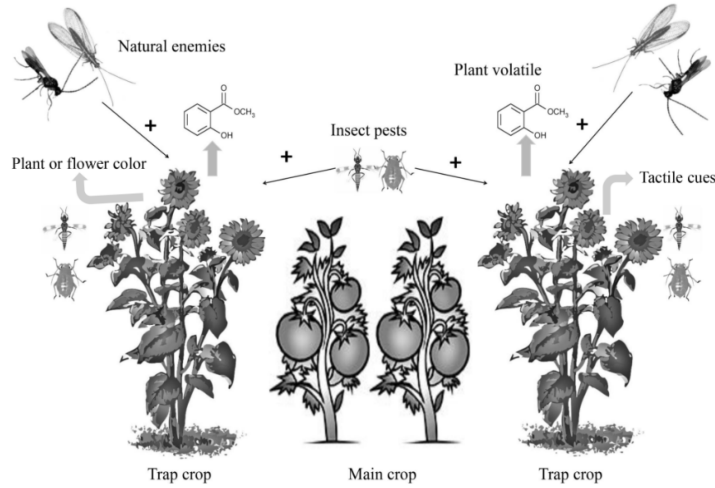


Figure 1: From Sarkar et al. (2018). ‘Role of trap crop to attract insect pests and natural enemies in a farming system.’

As explained by Fabarez et al. (2023) and by Fabarez (2023) (www.itbfr.org), various crops have been tested since 2021: spring oats and barley showing the most promising results to reduce aphids’ population at this point.

This work has therefore paved the way for additional information regarding the feasibility and sustainability of implementing the ‘companion plants’ solution should it be used to mitigate the economic risk associated with virus yellows infections in sugar beet fields. Using 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), as well as the model described in 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 aphids’ presence in the fields. After defining the break-even loss above which beet losses are sufficiently big to make the use of companion plants economically viable, we show that the impact of a reduction in aphids’ number is not linear. Consequently, a 23% decrease in aphids’ number, as triggered by the companion plants, does not result in a 23% reduction of beet losses.

1 Two reasons for economic non-viability

1.1 Efficiency and costs of the solution

The primary effect to be factored in our study is the reduction in aphids’ number triggered by companion plants which is expected to lower sugarbeet infections by virus yellows. The second aspect refers to the costs of such solution which includes planting and destruction of companion plants as well as the inclusion of an estimated beet yield loss resulting from competition between companion plants and sugar beets in the fields. The net cost-benefit value BC_{PC} could then be written as follows :

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

where ℓ is the virus yellows beet loss without companion plants, ℓ_{CP} is the virus yellows beet loss with companion plants, C_{ICP} is the combined planting and destruction cost of companion plants, and C_{CCP} is the reduction in beet yield loss due to competition between companion plants and sugar beets. Obviously, if there is no virus yellows beet loss, there is no companion plants’ benefit. BC_{PC} can 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 (at 16% sugar content) per hectare together with a price of € 45/ton of beets and considering an estimated average cost for the planting and destruction of companion plants amounting to € 97/ha (results from the project DEFT run by ARTB), the total expected beet revenue is € 3600/ha while the companion cost for planting and destruction (CICP) represents 2.7% of this expected beet revenue per ha).

As reported by Fabarez (2024), pilot trials run at the farm allowed to test various solutions. Three crops: oats, spring barley and faba beans were tested as companion plants. Companion plants were tested with and without pesticides, paraffin oil, and *Lecanicillium muscarium*. Amongst those crops, oats showed the most promising results, especially when destroyed once sugar beets at a 6-leaf stage, with an average 23% reduction in aphids' number (noted ξ). In the meantime, beet yield losses due to competition with companion plants represented 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, it is then possible to calculate the minimum beet loss level that equals the cost of using the companion plants (later referred to as the break-even loss). For $BC_{PC} = 0$ or $\ell - \ell_{CP} = C_{ICP} + C_{CCP}$ and total costs (aggregating competition effect costs and planting/destruction costs) of $108 + 97 = 205$ €/ha, the break-even loss is € 891/ha or 24.8% of the expected beet revenue per hectare (€ 205/ha being 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 show that estimated beet losses never exceed the 24.8% break-even loss for the Polerovirus (BMYV). In other words and under our cost-benefit assumptions, the companion plants have no positive economic impact when sugar beets are infected by Polerovirus.

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

1.2 The impact of a reduction in aphids' abundance

1.2.1 Main 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 infections (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

² Considering all oat trials, the efficiency of companion plants allowed a 36% reduction in aphids' number, but with an average beet yield loss of over 9% (Figures 2 and 9 of Fabarez (2024)). The costs of companion plants would therefore be € 421/ha (€ 324+97/ha or 11.7% of the expected beet revenue per ha and the break-even loss would represent 1169/ha (or 32.48% of the expected beet revenue per ha). Assuming that in the future we can optimize the use of the companion plants to get a maximum efficiency of 36% and a minimal loss due to competition of 3%, the break-even of loss to reach may eventually be 15.82% and could be reached with a 10.8% probability of occurrence over the period [2025-2100].

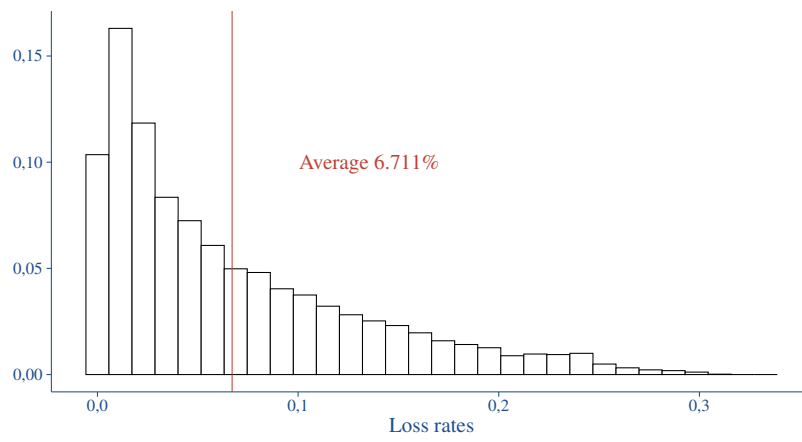
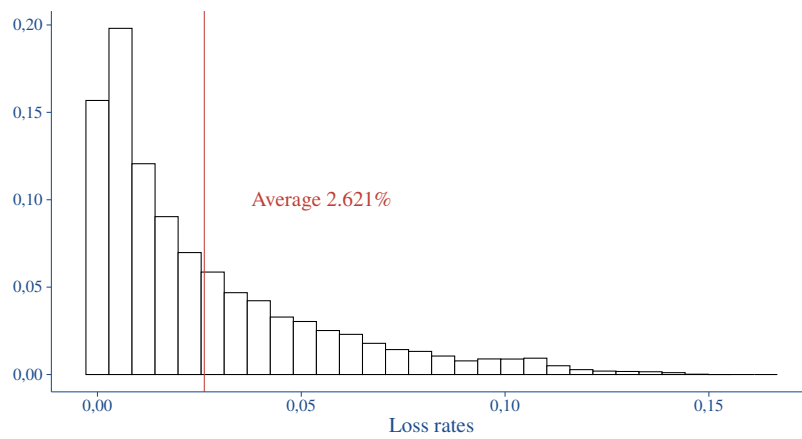


Figure 2: BMYV (top) and BYV (bottom) beet loss density over 2025-2100 (weighted by expected crop value).

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:

$$P = 1 - e^{-pN} \quad (1)$$

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.

In this investigation the infection cycle is initiated at time t_0 , when $Y_0 = 0$ 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*) migration in spring, and at this point, the proportion of infected plants, denoted as Y_0 , is set to be zero.

Last but not least, losses depend on the beet phenological stage when the virus is inoculated by aphids. The more mature the plant is, the more resistant it becomes and the lower beet losses will be. Furthermore and as highlighted in Figure 3, in the case of early infections, a plant infected by BMYV will suffer a loss of about 30%, whereas in the case of BYV the loss will be 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 same field even if it is eventually infected and beets present similar yellow-leaf symptoms later in the campaign.

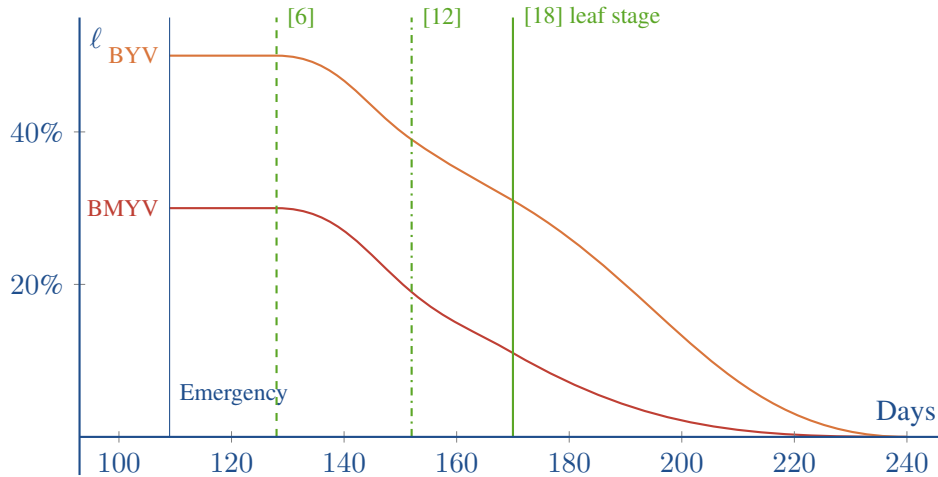


Figure 3: Expected beet yield losses ℓ due to Polerovirus (dark orange) or BYV (orange) infections relative to this beet phenological stages. On this figure, the number of days required to reach the different phenological stages – emergency (blue), [6]-leaf, [12]-leaf and [18]-leaf (green) - have been determined in accordance with results obtained from simulations run over the (2025-2100) period.

1.2.2 Abundance and first aphids' flights impact on incidence and losses

The equation 2 shows that incidence is a non-linear function of abundance and first aphids' flights. In addition, while the number of new infections increases, the rate of beet losses decreases as the plant matures and becomes more resistant. It is therefore hard to determine how a 23% reduction in aphids' number will exactly result when expressed in beet yield losses at the end. The aim of this section is to clarify the relationship between the reduction in aphids' numbers and the reduction in beet yield losses. From a methodological point of view and as stated on Figure 5, the number of days required by beets to reach a certain phenological stage are based on the number of average days calculated over the future 2025-2100 period. As recommended by ARTB (Phéllippé-Guinvarc'h and Cordier, 2023), the

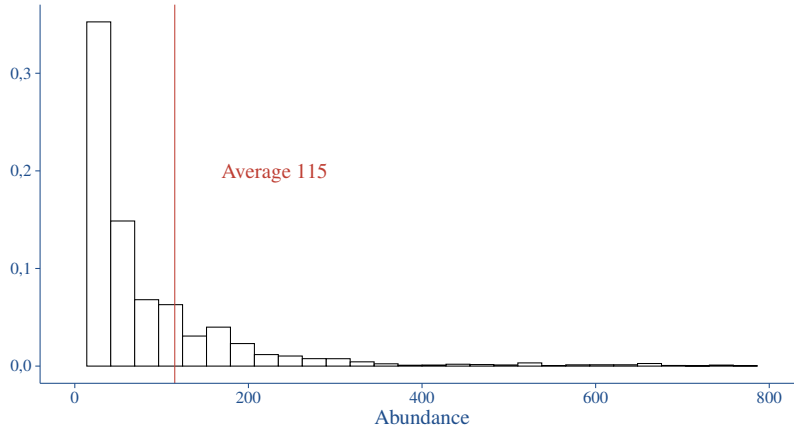


Figure 4: Abundance density 2025-2100 (weighted by expected crop value and where Abundance < 800)

assumption of Q_i for the northern region is, to date, the most appropriate in the French context and was then used for our modeling work.

Figure 5 shows the relationship between beet losses and aphids' abundance with and without companion plants. The top-left graph shows that the beet losses increase with the aphids' number, and that the reduction in aphids' number due to the use of companion plants (dotted line) also reduces losses. The top-right graph shows the efficiency of the companion plants. 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 aphids' abundance has an effect on beet yield losses 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 aphids' abundance is, the less effective the companion plants are.

If we carry out the same exercise on the first aphids' flight in Figure 5 only day values between 109 and 128 are plotted. This has to do with the fact that if the first aphids' flight occurs earlier than that they cannot land on beets and if it occurs after that, companion plants have already been destroyed (the [6]-leaf stage having been reached already). The bottom-left graph shows that the earlier first aphids' flight happens, the higher beet losses are. The bottom-right graph on the other hand, shows that companion plants are less effective when first aphids' flight happens early. The conclusion is therefore the same, the greater beet losses are due to early aphids' flights, the less effective companion plants are.

For the entire MPI scenario (IPCC 8.5), we calculated the beet losses with companion plants 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 results showed that the probability of $\ell_{CP} < \ell$ is equal to 0.

2 Discussion

Our cost-benefit analysis of companion plants as a way 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 infections may justify the use of companion plants and result in a positive economic result when compared to do nothing. We found that the use of companion plants is too costly (5.7% of income per hectare) when compared to expected virus yellow beet losses (2.621% for BMVY 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 on the beets: a time at which the estimated efficiency of companion plants is the lowest.

Of course, these results are conditional to the quality of the Q_i model and to the quality of the cost-benefit assumptions that have been used. As for the Q_i model, its use as a reference for many projects of the French national research program surely calls for its use by the GRECoS project project

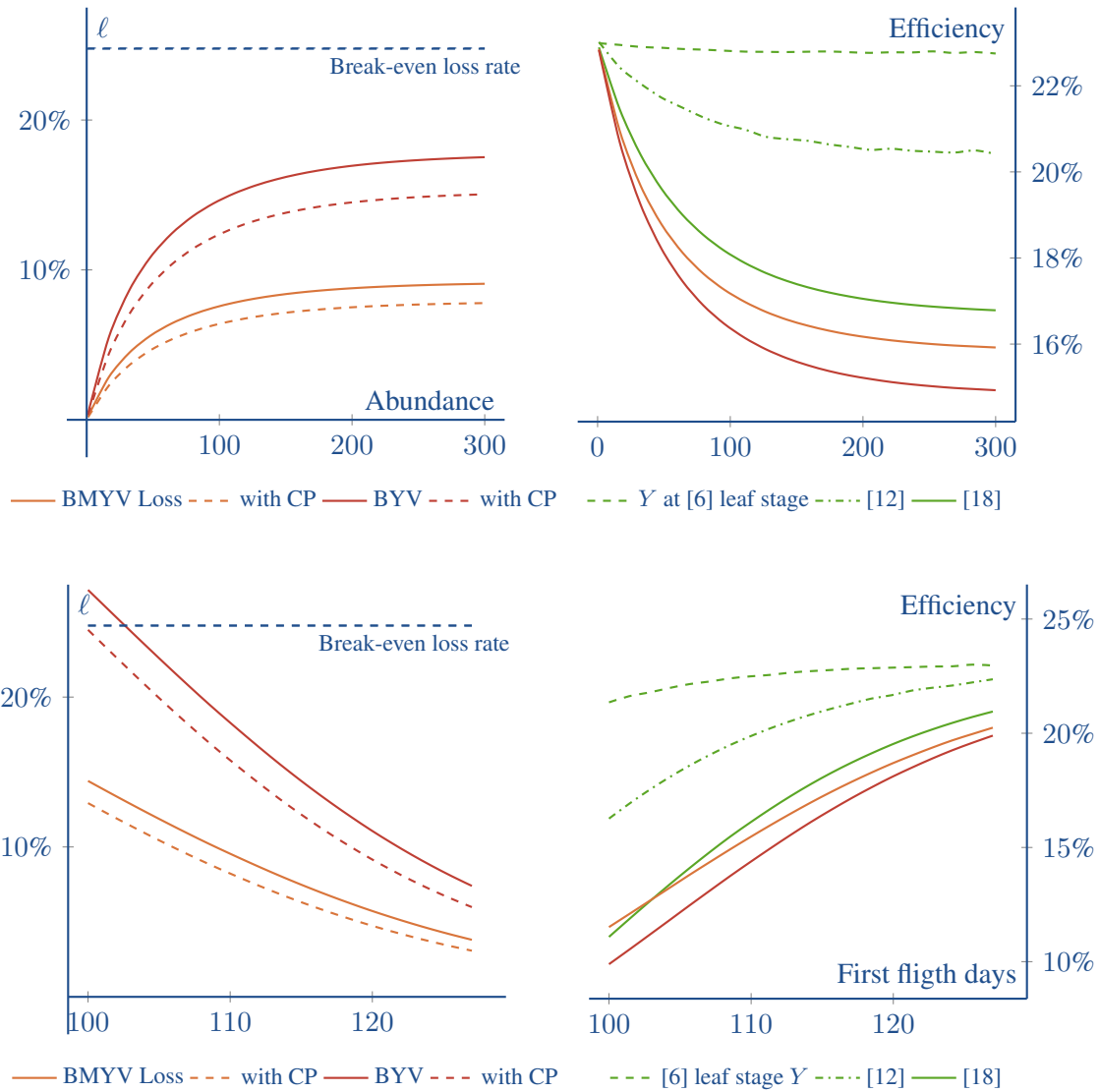


Figure 5: **At the top :** the effect of abundance on the loss ℓ and the incidence Y . On the left, the figure shows that the beetle losses that depends on abundance without (lined) and with (dashed) companion plants. On the right, the efficiency of reducing incidence (green) and losses (oranges) is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

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

(this publication arising from the work performed in this project) although some theoretical aspects of it may be questionable. Regarding the estimation of the full cost of companion plants, it has been set to an optimal level as we only considered 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) who used machine learning to identify risk factors for virus yellows spreading in sugar beet fields. 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 aphids' 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.

Meanwhile, one notable aspect of the work done by Fabarez is: the variability in companion plants' performance or efficiency. This is also the case for other alternatives to neonics proposed by Laurent et al.. Although introducing such variability could have allowed us to identify certain cases where the reduction in beet yield losses due to the companion plants was better than average, this would also have included 22% cases where companion plants would have been far less efficient than average. Integrating this variability would therefore have meant adding a risk premium to the full cost of the measure, thus increasing the break-even loss level of the companion plants.

Although the results may seem rather disappointing, companion plants can be considered in synergy with other solutions, for example by using odor repellent measures. Synergy between two solutions could indeed improve efficiency or generate significant positive externalities, such as soil enrichment or improved plant resistance to other risk factors. But while all the literature consulted unanimously stresses the need to combine technical solutions to combat the development of beet yellows, they should be subject to an economic and operational cost-benefit analysis. As Fabarez explained: 'It has been difficult to select and massively deploy trials that combine multiple levers (or solutions) because of the lack of efficiency from 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 is to provide a cost-benefit analysis based on modelling work. Although 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, this study work calls for further simulations to be done using other technical or combined solutions. These new and/or combined solutions may significantly reduce the number of aphids landing on sugar beets and transmitting virus yellows, or have other effects such as reducing implementation costs or providing other valuable positive externalities which could be valued economically and therefore change the economic equation of the solution.

2.1 Acknowledgment

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2.2 Funding

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Recherche Technique Betteravière (ARTB). The GREcoS project aims at prefiguring what risk management system would be the most appropriate to cover beet yellows risk using alternative technical solutions to the neonics which are developed by other projects of the PNRI.

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