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RESEARCH ARTICLE

Estimating farmers' net change in profit when using insect frass as an input for *Brassica* crops

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Abstract

This research addresses a knowledge gap in understanding the economic feasibility and ecological benefits of frass in circular agriculture. Its primary objective is to estimate the net change in profit that farmers can expect by adding insect frass to their array of crop and soil health promoters used in *Brassica* production. As such, the study contributes to estimating the role of circular agricultural practices in promoting environmental sustainability and economic efficiency. Assuming applications of frass occur in the current season, in four years and again in eight years, frass is expected to consistently generate an increase in net profit in *Brassica* production. Specifically, conventional broccoli production having the highest increase and conventional Brussels sprouts production the lowest increase. Frass is expected to be economically justifiable, even attractive over the years for farmers. While reducing the need for alternative chemical pesticides, frass could contribute to improved soil life and quality. It facilitates balanced and efficient plant growth and contributes to the plant's systemic resistance to pests and diseases. Frass offers opportunities for arable farmers who are expected to achieve higher profits while using less chemical inputs.

Keywords

circular economy – expert elicitation – innovation adoption – partial budget – stochastic simulation

1 Introduction

Shifts in practices to integrate more environmental approaches are becoming increasingly considered within the agriculture sector. This is evident in farms and other production facilities across various sectors, which typically produce by-products alongside their main products, leading to an accumulation of residuals. In response, there is an increasing adoption of circular production systems. These systems emphasize the recycling and repurposing of by-products, aiming to efficiently utilize resources while managing the build-up of residuals (Geissdoerfer *et al.*, 2020). Agriculture is one of the sectors moving towards circularity as opportunities for by-product recycling become more apparent (Dagevos and de Lauwere, 2021).

One opportunity for circularity in agriculture exists between insect producers and arable farmers. Insect production generates frass, consisting of several by-products – molted exoskeletons (exuviae), manure and undigested feed. Insect frass, particularly from the black soldier fly (BSF), presents a promising and environmen-

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tally friendly alternative to traditional fertilizers due to its rich chemical-physical characteristics and sustainable production process (Elissen *et al.*, 2023). BSF frass, dependent on the substrate used, typically contains higher organic matter than compost and various manures, with significant macronutrient content and a favorable carbon-to-nitrogen ratio (Elissen *et al.*, 2023). The production of BSF frass contributes to waste reduction, enhanced soil health, and decreased greenhouse gas emissions by recycling organic waste into valuable protein feed and organic fertilizer (Beesigamukama *et al.* 2022). For example, BSF frass has been shown to effectively support plant growth while reducing nitrogen leaching, thus promoting more sustainable agricultural practices (Beasley *et al.*, 2023). Additionally, frass can improve soil microbial biomass and nutrient cycling, benefiting overall soil health (Watson *et al.*, 2021). In Europe, the production, storage, and utilization of insect frass are regulated under Regulation (EU) 2021/1925, which includes standards for heat treatment and microbiological safety, ensuring its safe use as an organic fertilizer (IPIFF, 2023). These combined advantages underscore the potential of BSF frass in contributing to a circular economy and enhancing sustainability in agriculture.

Frass offers an interesting benefit for crop farming. For instance, it can be recycled as a crop and soil health promoter for use on arable farms (Barragán-Fonseca *et al.*, 2022). For example, given that frass is composed of organic matter, it can be used to supplement the nutritional needs of the crops and soil (Chavez and Uchanski, 2021; Kebli and Sinaj, 2017; Quilliam *et al.*, 2020; Temple *et al.*, 2013; Vickerson *et al.*, 2017). Additionally, frass also exhibits potential added value as a crop and soil health promoter. Research conducted by Bai (2015) showed that when exuviae are integrated into the soil, Bacilli colonization increases by more than fifteen percent after seven weeks. By stimulating specific beneficial microbial groups (e.g. *Bacillus* or *Pseudomonas* species), frass can interfere with the performance of various herbivores and suppress various diseases (Andreo-Jimenez *et al.*, 2021; Cretoiu *et al.*, 2013; Kupferschmied *et al.*, 2013; Laurentis *et al.*, 2014; Randall *et al.*, 2020). With fewer pests and diseases present, less crop yield loss would occur. Ultimately, frass could potentially reduce the reliance on chemical insecticides and fungicides while improving crop yield. Researchers continue to test the effectiveness of insect frass as a crop and soil health promoter, though more time is needed to determine its full potential (Barragán-Fonseca *et al.*, 2022).

For frass to play a role in circular agriculture, it should be economically justifiable for farmers to use it. A comprehensive overview of frass' influence on the pests, diseases and yield for any one crop is currently lacking. Likewise, there is currently no reliable indication of the extent in which frass can reduce the need for chemical crop protection products. The objective of this research is therefore to estimate the net change in profit that farmers can expect by adding insect frass to their array of crop and soil health promoters used in *Brassica* production. Some of the most recent (and ongoing) research regarding frass' effectiveness as a crop and soil health promoter stem from experiments that use *Brassica* crops; we therefore examine *Brassica* production to best align with these experiments. To meet the objective, three underlying research questions are addressed:

When applying insect frass in *Brassica* production as a crop and soil health promoter compared to not applying frass,

1. by how much is pest and disease presence expected to change?
2. by how much is crop yield expected to change?
3. by how much is fungicide and insecticide use expected to change?

Experimental research data are not (yet) available to answer our research questions. Therefore, we decided to consult experts. Relying on expert knowledge provides an opportunity to gain insights into insect frass' performance by extrapolating results from the most recent and on-going studies. Because the current scientific literature provides an insufficient overview of frass' potential, expert elicitations aid in gaining insights into topics beyond the current knowledge base (Morgan, 2014).

Our research focuses on the use of insect frass in the Netherlands because a great deal of insect production and the development of insects for food and feed occurs in the Netherlands (van Huis, 2013). Additionally, research investigating insect frass' effectiveness against various pests and diseases in *Brassica* crops is currently taking place in the Netherlands.

We investigate the net change in profit for two *Brassica* crops (broccoli and Brussels sprouts). *Brassica* crops vary greatly in terms of the extent of pesticide use and how long the crops are on the fields. Among the *Brassica* vegetables, broccoli production utilizes very few active crop protection product ingredients, while Brussels sprouts production utilizes many (KWIN-AGV, 2018). Considering these two extremes is therefore useful for comparing insect frass' potential economic effects within *Brassica* production. We consider both conventional and organic production as the allowance for pes-

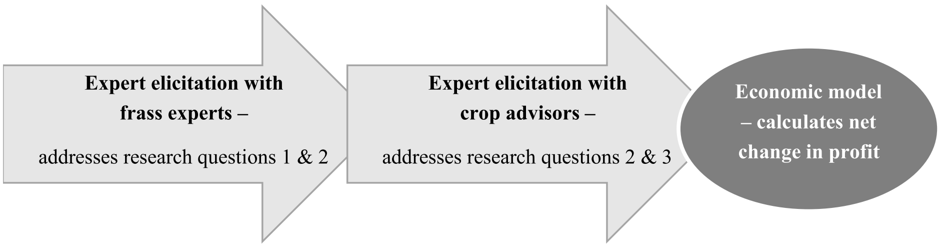

FIGURE 1 The three-step process applied in this study.

ticide usage and application schemes differ between the two systems.

2 Methods

Our approach consisted of three parts: (1) elicitation with frass experts, (2) elicitation with crop advisors and (3) the construction of an economic model. Results from the first expert elicitation were discussed with the experts in the second elicitation. The results from the second expert elicitation served as input for the economic model. This model was then used to calculate the net change in profit farmers may expect when utilizing frass compared to continuing their normal practice – the baseline scenario. Figure 1 summarizes the three-step research process.

Expert elicitations

The first two steps in our research approach were expert elicitations. The first expert elicitation consisted of structured individual interviews followed by a group discussion with insect frass experts. The aim of this first elicitation was to address research questions 1 and 2. Insect frass experts were defined as researchers conducting and/or supervising experiments on the effects of insect exuviae (molted skins) or frass on crop and soil health at Wageningen University & Research. Seven frass experts participated in the interviews, of which six then also participated in the subsequent group discussion. During the interviews, experts provided estimations of frass' effectiveness towards fourteen pests and eleven diseases that are notoriously destructive and common in *Brassica* production (listed in Appendix A, Table A1) (Agriculture and Horticulture Development Board, 2017). More specifically, they provided lowest, highest and most likely estimations (in percentages) of how much they expect frass to influence (a) the presence of the specified pests and diseases and (b) crop yield in organic and conventional broccoli and Brussels sprouts production. They also gave explanations justifying their estimations. During the subsequent group discussion, experts were presented with a summary of the estimations and explanations given during the interviews. For each pest and disease, experts shortly discussed the summary, after which they provided new individual estimations (via an anonymous online survey).

The results of the first expert elicitation were used as a reference for the experts in the second expert elicitation. This second elicitation consisted of individual interviews with crop advisors. The aim was to address research questions 2 and 3. Crop advising experts were defined as people who are hired by farmers for providing advice based on their experience with broccoli and/or Brussels sprouts organic/conventional production in the Netherlands. Three crop advisors participated. The experts provided estimations of frass' ability to reduce the use of insecticides and fungicides sourced from KWIN-AGV (2018) (listed in Appendix A, Table A2). More specifically, they provided lowest, highest and most likely estimations (in percentages) of how much they expect frass to influence (a) the use of specified insecticides and fungicides and (b) crop yield in organic and conventional broccoli and Brussels sprouts production. They also gave explanations justifying their estimations.

All individual interviews were conducted based on carefully developed and pre-tested interview guides. The group discussion in the first expert elicitation was conducted according to a predefined protocol. Relevant assumptions were established and presented to all experts (see Box 1). The assumptions specified, among other aspects, soil type, weather conditions, and a four-year crop rotation. The assumed four-year crop rotation scheme was taken as an average of reported crop rotation designs involving broccoli (e.g. Velazco, 2013), such as three-year designs (e.g. with clover and grain) and four-year designs (e.g. with potato, legumes, and carrot), and was validated by the crop advising experts. Including the crop rotation was necessary to capture how the net change in profit may differ from year to year as frass' health promotion effects are expected to change over time (Torgerson *et al.*, 2021). Experts' estimations

Box 1 – Assumptions

Consider that a farmer has a crop rotation where he will be planting broccoli and Brussels sprouts this year (which is referred to as year 0), in 4 years and again in 8 years.

Assume:

(1) it is allowed by legislation to apply insect frass to fields, and it is abundantly available,
(2) the farmer will add insect frass at the ideal application dose each year (now, in 1 year, in 2 years, etc.),
(3) consistently ideal weather conditions,
(4) a 1-hectare plot of land with an annual crop rotation of broccoli and Brussels sprouts (50:50) – potatoes – sugar beets – wheat and
(5) the soil type is clay.

were elicited for the *Brassica* crops for year 0 (indicating how it is used now, in the current year), and then again in four years and finally after eight years. Notably, the term "frass" was discussed in a general context with the experts. This decision stemmed from the fact that the participating experts had been researching frass and exuviae from various insects, including black soldier flies, crickets, and mealworms. They expressed discomfort in extrapolating findings from a single type of frass, as their research did not focus exclusively on one insect. Thus, we collectively agreed to use the broader term "insect frass". We refer to the supplementary material for a more in-depth explanation of the methodological procedures of the expert elicitations.

Economic model – a partial budgeting exercise

We developed an economic model that calculated the expected net change in profit for farmers by comparing two scenarios: a baseline and an alternative scenario. The *baseline scenario* was defined as a representative year of Dutch *Brassica* production, in which organic and conventional pesticides are utilized. The *alternative scenario* was defined as a representative year of Dutch *Brassica* production, in which, in addition to the organic and conventional pesticides that are utilized, frass is also applied. Notably, the applications of pesticides in the alternative scenario can be lower than in the baseline scenario. This is because frass is expected to promote the health of crops and soil and is therefore also expected to decrease the quantities of organic and conventional pesticides applied. The analysis we conduct is referred to as a partial budget, as only the differences in costs and revenues between the two scenarios are considered while all other aspects of the business are considered to remain the same (Kay *et al.*, 2012). Separate partial budgets were made for each year (years 0, 4, and 8). Net change in profit was calculated at these three points in time to estimate the differences in expected profit.

The net change in profit (in Euros per hectare) observed when comparing the baseline scenario to the alternative scenario was calculated according to the following model:

$$\Delta P = R_A + C_R - C_A \tag{1}$$

where ΔP is the net change in profit, R_A is additional revenue, C_R is reduced costs, and C_A is additional costs (all in Euro / hectare). The different terms are further defined as

$$R_A = Y p_S c_Y \tag{2a}$$

$$C_R = p_P Q_p c_p \tag{2b}$$

$$C_A = N p_F D_F \tag{2c}$$

where Y is crop yield (head / hectare or kg / hectare),[1] p_S is sales price (Euro/head or Euro/kg)[1], c_Y is change in crop yield (%),[2] p_P is price of pesticide (Euro/kg or Euro/l)[1], Q_p is quantity of pesticide applied (kg/hectare or l/hectare)[1], c_p is change in pesticide use (%)[2], N is number of plants planted (seedling plants / hectare)[1], p_F is price of frass (Euro/kg),[3] and D_F is dose of frass (g frass / seedling plant / 1,000 = kg frass / seedling plant)[3].

Below, we discuss each term equations (2a-c) in more detail. Furthermore, Figure 2 provides a visual overview of how the multiple data sources are integrated into the model, which will also be discussed in further detail below.

The economic model was built under the assumptions presented in Box 1. The development of the baseline scenario for the partial budget model required data from the KWIN-AGV (Kwantitatieve Informatie – akkerbouw en vollegrondsgroenteteelt; or quantitative information – arable farming and field vegetable cultivation), which contains Dutch agricultural financial data (KWIN-AGV, 2018). More specifically, KWIN-AGV provides an overview of the expected crop yield and quantities and prices for insecticide and fungicide applications

1 Fixed, baseline inputs from KWIN; see Appendix B.
2 Elicited estimations represented by PERT distributions.
3 Estimations represented by triangular distributions.

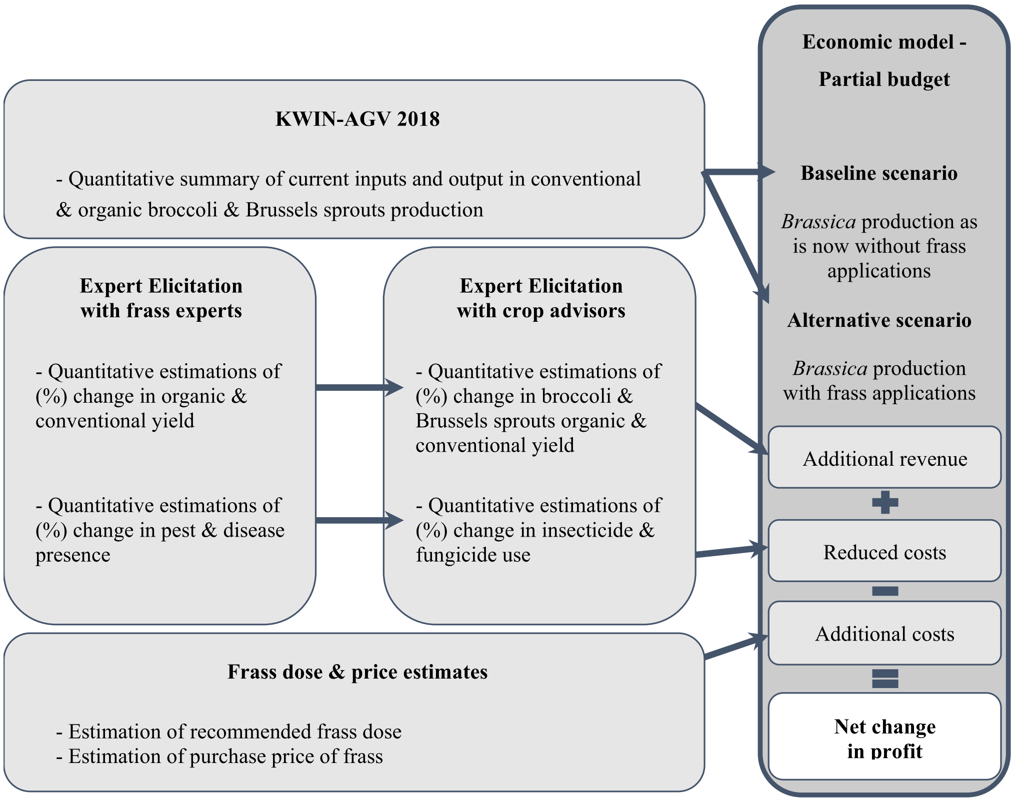

FIGURE 2 The flow of data and its use in the partial budget.

for organic and conventional crops. Appendix B provides an overview of the parameters that defined the baseline scenario.

Additional revenue (R_A)
Frass may reduce the presence of certain pests and diseases not yet addressed by currently used insecticides and fungicides. As such, additional revenue would be generated from less crop loss. The additional revenue was calculated from the crop advisors' averaged lowest, most likely and highest estimations for each crop and for each of the three years considered. Program Evaluation and Review Technique (PERT) distributions were used to represent the averaged lowest, most likely and highest estimates regarding the expected changes in crop yield (in percentages) elicited from the crop advisors with the most weight again attributed to the average most likely estimates. PERT distributions are bell-shaped curves that utilize minimum, maximum and most likely estimates (Malcolm *et al.*, 1959). Such distributions incorporate a weighted mean (μ) where we attribute the most weight to the averaged most likely estimations.

Reduced costs (C_R)
In the alternative scenario, some of the production costs may be lower than in the baseline scenario. For instance, as frass could reduce the presence of various pests and diseases, the costs related to insecticides and fungicides could decrease. Specifically, the estimations provided by the crop advisors regarding reduced insecticides and fungicides were integrated into the model. To do so, the lowest estimates were averaged, as were the most likely, and finally the highest. A PERT distribution was chosen to represent the range of estimations.

Additional costs (C_A)
To calculate the additional cost of applying insect frass to the land, two variables were considered: the necessary dose and the purchase price of frass. There is no determined dose of insect frass required to achieve the expected health promoting effects. However, in the experiments conducted by the participating frass experts, doses of one, two and five grams of frass per kilogram of soil were tested where one plant occupied one kilogram of soil. These three doses were integrated into the model using triangular distributions. We opted for a triangular distribution because it is a common choice when there is only limited data available (in this case, a limited number of expert evaluations) with some

uncertainty, it is assumed there is one maximum, and one wants to avoid negative values.

Though insect frass is not readily available on the market, there are a few existing exceptions (marketed as "soil improvers" or fertilizers). Prices of frass (based on black soldier fly[4]) in the Dutch market as of June 2022 range from €1.20-€2.85 per kilogram. To capture the range of prices, three prices of frass were used in the model – €1.00, €2.00 and €3.00 per kilogram of frass. Triangular distributions were used to reflect the three prices in the partial budget.

Reduced revenue

Compared to the baseline scenario, the alternative scenario was not expected to result in any reduced revenues. Therefore, no reduced revenues were considered in the partial budget.

Factors not included in the model

Reduced costs due to frass reducing the amounts of compost applied were not considered. Compared to spreading manure or composts (>50 tons/hectare), the contribution of frass in the doses considered is relatively small (<0.2 tons/hectare). As such, the organic matter contribution of frass would have a negligible influence on the amount of compost that would be applied in the baseline scenario.

We do not account for increased or reduced labor needs. As the proposed doses of frass were all less than two hundred kilograms per hectare, such quantities could be applied in the same pass as planting. Similarly, if frass eliminates any late season sprays, reduced costs of the same variables should also be accounted for. Costs of labor were not included as there was not enough information available regarding how frass would be applied and the mechanical implications of its distribution on the field.

Finally, the costs and revenues associated with utilizing insect frass throughout each year of the crop rotation were not estimated. There currently is not enough known regarding frass' performance in other crops to do so.

Software implementation

The partial budget was created in Excel version 2102 (Microsoft Corp., Redmond, WA, USA) along with the commercially available Excel add-in Palisade @Risk version 8.2 (Palisade Corp., Ithaca, NY, USA), a specialized add-in for risk assessments. This add-in assigns a specified distribution to each input variable to quantify the uncertainty around the outcomes.

Using @Risk, a simulation was conducted with one thousand iterations. Sampling was conducted using the Latin Hypercube method to avoid sampling bias (McKay *et al.*, 1979). The net change in profit was simulated for each type of crop (organic and conventional broccoli and Brussels sprouts) for each of the three years resulting in twelve cases. A positive result indicated that the net change in profit is higher in the alternative scenario than in the baseline scenario; whereas a negative result indicated that the net change in profit is lower in the alternative scenario than in the baseline scenario.

Two additional measures were taken to account for the uncertainty from the experts' estimations. First, a 90% confidence interval was calculated with the net change in profit. Second, a sensitivity analysis was performed using tornado graphs generated in @Risk. These graphs show which variables contribute the most uncertainty to the mean outcome, which in our case was the net change in profit. Note that no correlations were conducted among the random variables in the analysis as there was not enough data to justify a correlation matrix.

Finally, a worst case scenario was also calculated to produce a complete overview of the possible outcomes. The worst-case scenario was calculated by utilizing the following inputs: (1) the highest dose scenario (five grams of frass/plant), (2) the highest price scenario of frass (€3.00/kg), and (3) the most pessimistic estimates provided by any of the experts.

3 Results

First presented in this section are the results from the expert elicitations with frass experts and crop advisors in the section "Expert elicitations". After, in section "Economic model", the results from the economic model are presented.

4 Price sources for referencing included (but were not limited to) the following webshops: Amazon.nl. Frassor Insecten Frass. Available at: https://www.amazon.nl/Frassor-Insecten-Frass-Alles-%C9%E9n/dp/B0CR1DXD8J. Accessed July, 2022. Frassor. Webshop – Insecten frass. Available at: https://frassor.com/nl/webshop/. Accessed July, 2022. Organifer. Insectenmest korrels – Black Soldier Fly Frass. Available at: https://organifer.com/nl/p/insectenmest-korrels-black-soldier-fly-frass-20kg-voor-200m2. Access July, 2022. SaltonVERDE. Insect Frassmest zwarte soldatenvlieg | Lurpe. Available at: https://saltonverde.com/nl/producto/insect-frass-lurpe/. Accessed August, 2022.

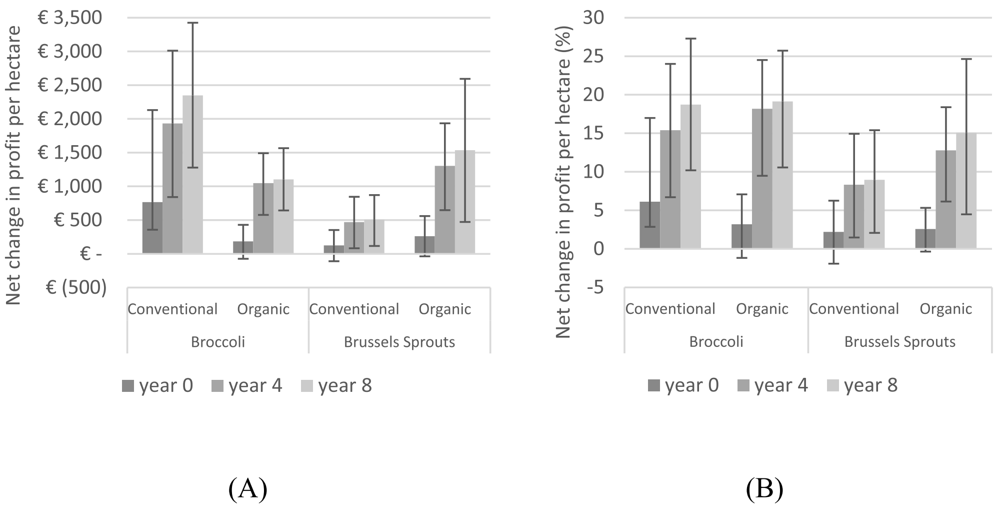

FIGURE 3 (A) Expected net change in profit per hectare with frass application compared to no frass application. (B) Percent expected net change in profit per hectare with frass application compared to no frass application.

Expert elicitations

Appendices C-E (Figures C1, D1 and E1) provide a summarized, quantitative overview of the expert elicitation results. The graphs share the general trend that the experts believe that frass' effects improve overtime; reductions in pests, diseases, insecticides and fungicides are greatest in year 8 and lowest in the first year. Similarly, increases in crop yield are estimated as highest in year 8 and lowest in the first year. Frass experts explained that the anticipated improvement over time is mainly due to the functionalities of frass and its influence on the microbial communities in the soil. As farmers' use of chemical pesticides reduces and the populations of natural enemies begin to build-up in the soil, more beneficial effects of frass can be expected. Therefore, it takes time for the soil's environment to become optimal.

On average, pests were expected to be reduced by 0-15% in the first year and by 2-23% in year 8 (Appendix C). Insect frass experts mentioned that frass will be most effective against pests that induce jasmonic acid pathways. As such, conventional insecticides were expected to be reduced by 0-10% in the first year and by 10-40% in year 8. Organic insecticides showed even higher average reductions (Appendix D).

Disease and fungicide reductions were even slightly more promising. Diseases, on average, were expected to be reduced by 9-18% in the first year by 11-24% in year 8 (Appendix C). Insect frass experts mentioned that frass could delay the onset of (especially soil-borne) diseases. As such, fungicides were expected to be reduced by 5-10% in the first year and by 18-40% in year 8 (Appendix D).

Frass experts expected that frass will reduce the amount of crop lost to caterpillars; crop advisors noted that damage resulting from caterpillars on average renders crops unsellable. Therefore, with less damage from caterpillars, less crop would be lost. Thus, due to less loss from pests and disease, conventional yield was expected to improve, on average, by 3-8% in the first year and by 6-16% in year 8. Organic yield was expected to improve, on average, by 3-9% in the first year and by 13% in year 8 (Appendix E). The higher yields achieved in conventional production can be attributed to the difference in pesticide allowance between the two systems. As an example, crop advisors mentioned that in a representative year, little of the conventional Brussels sprouts crop is lost, especially compared to organic production. Of the 33,300 plants planted per hectare in both systems, organic producers harvest 9,000 kg of sprouts whereas conventional producers harvest 25,000 kg.

Economic model

Figure 3a depicts the expected net change in profit in conventional and organic broccoli and Brussels sprouts production in years 0, 4 and 8. Figure 3b shows the expected net change in profit divided by the profit obtained in the baseline scenario (provided in Appendix B). The shaded bars indicate the expected net change in profit per hectare. For each shaded bar, an error bar is also drawn from percentiles 5% and 95% thus indicating the expected net change in profit with 90% certainty. The length of the error bars is primarily attributed to frass' expected influence on crop yield as was determined in the tornado graphs of the sensitivity analysis. See Appendix F for an example of the generated tornado graphs.

Figure 3a,b shows that the expected net change in profit in the alternative scenario for each form of production is positive, which implies that using insect frass in combination with the various organic and conventional pesticides results in a higher net profit than a normal production system that does not utilize frass. However, considering the confidence intervals, the first year in which frass is used has a chance of returning a negative net profit in three of the four production types. Over time, however, the use of frass is expected to return positive a net change in profit (also at a 90% confidence interval).

Broccoli

Figure 3a shows that the net change in profit when adding frass in conventional broccoli production is about double of that in organic production. One reason is because the frass experts expect that frass will reduce the amount of crop lost to caterpillars. Crop advisors noted that the damage caused by caterpillars to the broccoli's head often renders crops unsellable. Figure 3b shows that, in terms of change in percent profit, organic and conventional broccoli production are comparable. Granted, the first year of organic production can return a negative profit based on the 90% confidence interval. The differences between organic and conventional production can be mostly attributed to the difference in crop yield obtained in the baseline scenario. Conventional producers harvest about €15,000 worth of broccoli per hectare; organic producers harvest about €9,000 worth of broccoli per hectare. Therefore, a percent increase in yield has a larger relative impact on profit for conventional production than in organic production. It is useful to note that though frass is expected to influence the amounts of insecticides and fungicides used, financially, the impact of these reductions is minor compared to the financial influence of increasing crop yield.

Brussels sprouts

Figure 3a,b show that, in the first year, the net change in profit in Brussels sprouts is comparable between conventional and organic production. By years 4 and 8, the net change in profit is more than double for organic production. A few variables explain these trends. Though conventional Brussels sprouts obtain almost three times the crop yield than in organic production, organic producers receive almost four times the sales price per kilogram of sprouts. Notably also, conventional producers have higher costs in insecticides and fungicides than organic producers (KWIN-AGV, 2018). Therefore, though crop advisors expect that yield will increase in year 0 by 3% in both conventional and organic, the net change in profit is slightly higher in organic production.

TABLE 1 Worst-case scenario – net change in profit per hectare

	Broccoli		Brussels sprouts	
	Conventional	Organic	Conventional	Organic
Year 0	€ –592	€ –570	€ –547	€ –500
Year 4	€ –580	€ –555	€ –520	€ –492
Year 8	€ –590	€ –526	€ –559	€ –485

The results show that the net change in profit is lower in Brussels sprouts than in broccoli. The crop advisors noted that, compared to broccoli, Brussels sprouts' longer time spent on the field makes it more susceptible to pest infestations or diseases. Because frass would be applied at the time of planting (Torgerson *et al.*, 2021), according to the crop advisors, the chance it can reduce the need for late-season pesticide applications in Brussels sprouts is less compared to broccoli.

Worst-case scenario

The results of the worst case scenario show that, depending on the type of production and the year, there is a potential loss of €-592 to €-485 per hectare in net profit (see Table 1). At a dose of five grams of frass per plant and at €3.00 per kilogram of frass, the cost of purchasing frass for one hectare of land is €500 for Brussels sprouts and €570 for broccoli. Note, more broccoli is planted per hectare than Brussels sprouts (38,000 versus 33,300 plants), and therefore more kilograms of frass would be applied to one hectare of broccoli than one hectare of Brussels sprouts. Therefore, much of the loss shown in Table 1 can be attributed to the purchase price of frass.

4 Discussion

The objective of this research was to estimate the net change in profit that arable farmers can expect by adding insect frass to their array of crop and soil health promoters in *Brassica* production. This research shows that frass has potential as a crop and soil health promoter. As such, it makes the first attempt at quantifying the economic contribution that insect frass could deliver as a crop and soil health promoter. Such estimations are also an important first step for communicating the frass' potential as a circular agricultural input. Innovative solutions for recycling by-products in agriculture are needed for making the sector more circular. Insect frass is one such solution – connecting insect rearing with arable farming.

The results of this research show that insect frass is expected to generate a positive net change in profit for farmers. This finding aligns with that of Tanga *et al.* (2022), though notably they investigated frass' economic potential as fertilizer, not as a health promoter. Their results show that, in addition to mineral fertilizer, the frass treatment resulted in the highest maize yield and highest economic returns.

The results suggest that frass can potentially be most beneficial when applied in types of production that are on the field for shorter lengths of time and are susceptible to late season pests or diseases that are addressed by frass. In addition, the results suggest that by years four and eight, the net change in profit is estimated to improve by more than 2.5 times in conventional production and by more than 5 times in organic.

The uncertainty of applying frass, especially in the first year, should be considered. With the exception of conventional broccoli, in the first year of applying frass, potentially the net change in profit can be positive or negative. As shown in the sensitivity analysis (presented in Appendix F), the amount of uncertainty behind frass' influence on crop yield accounts for much of the error bars. More research that specifically investigates frass' influence on crop yield would be useful in reducing the uncertainty behind these findings.

For farmers to make a decision regarding whether or not to trial frass, they may rely on various decision tools. For example, for the more risk averse farmers, decisions on using new products may be based on the worst-case scenario – a safety first approach (Kay *et al.*, 2012). The worst-case scenario for using frass could result in a net loss in profit of €500 to €600 per hectare. If the worst-case scenario occurred on the trial plot, the farmer could face a profit loss of between 5% (in conventional broccoli and organic Brussels sprouts) and 10% (in organic broccoli and conventional Brussels sprouts). For this reason, a risk averse farmer may not be willing to trial insect frass. However, farmers that make decisions based on the option with the highest, most likely outcome would be more likely to trial the frass.

For those that would choose to trial frass, the first year applying it may also require some learning-by-doing experience from the farmer. For instance, frass can only be effective if the farmer bases pesticide applications on what is observed and determined as necessary during monitoring and not based on a strict spraying schedule. It is critical that the farmer is conscious of how frass is expected to perform. For example, knowing which pests and diseases it is expected to deter and knowing what parasitoids it is expected to be able to recruit would be required to monitor the crop effectively. With this awareness, the farmer can possibly eliminate later applications or act in instances when the frass is not performing as expected.

The economic insights provided in this study can help demonstrate frass' potential as a circular agricultural input also for policy development. In November 2021, the EU implemented a policy that standardized frass' processing procedure and permitted its use as an organic fertilizer (EU Commission, 2021). This research along with the continual inflow of new evidence regarding frass' effectiveness against various pests and diseases can be used to build a case for insect frass achieving more relevant and specified legislation that permits its use as an input on crop land.

Limitations, practical considerations and future research

This research makes a first attempt at valuing frass as a crop and soil health promoter, which required making numerous decisions. For example, we focused on broccoli and Brussel sprouts, but the effects of frass may be even more valuable in other sectors like tree nurseries or greenhouse vegetables. We also made assumptions that the weather conditions are ideal, and the soil type is clay. Modifying these assumptions would be expected to influence frass' effectiveness. Alternative types of cropping systems, like applying frass in strip cropping, may also influence its effectiveness. Furthermore, future research should explore the effects of frass under alternative assumptions.

In this research, we discuss insect frass generally. However, frass can vary in terms of the insect species reared or the feed the insects are reared on. Furthermore, some specific components of frass (e.g. the shed skins known as exuviae) show even more promising health promotion effects (Barragán-Fonseca *et al.*, 2022). All of these factors could have an influence on the performance of frass as a crop and soil health promoter. Once there is more understanding of how these components affect frass' performance, an economic feasibility should be conducted to understand their respective financial consequences.

It was assumed that frass would be available in the required quantities. If frass is deemed economically attractive in more forms of production, its availability may come into question. As the insect sector grows, more frass will be generated.

Finally, the construction and interpretation of the resulting net changes in profit rely on the estimations elicited from both the frass experts and the crop advisors. Interpretations of the results should therefore be made under the consideration of the limitations faced by the frass experts (e.g. extrapolating their knowledge from field experience and early research trials) and crop advisors (e.g. combining estimations from frass experts with their own experience with comparable products). To confirm the results of this research, farm trials should be conducted from planting to harvesting that measure pests, diseases, parasitoids and crop yield. Trials that investigate the effects in complete crop rotations over several years would also be required to validate the expected time-related improvements suggested in this research.

5 Conclusion

This research relied on experts' knowledge to estimate the net change in profit farmers can expect when using insect frass as a crop and soil health promoter in various types of *Brassica* production. We conclude that frass is expected to be economically justifiable, even attractive over the years for farmers. While reducing the need for alternative chemical pesticides, frass could contribute to improved soil life and quality. Doing so facilitates balanced, steady and efficient plant growth and contributes to the plant's systemic resistance to pests and diseases. Granted, frass will only perform for farmers that will implement it correctly in a crop monitoring scheme. The way towards sustainable food production in the future will require the abandonment of predetermined spraying regimens and the implementation of monitoring crops and reacting accordingly. In this way, chemical pesticides can be substituted for more sustainable inputs, and in the case of insect frass, they can be substituted for more circular inputs. Thus, insect frass offers a win-win situation for arable farmers who would be expected to achieve higher profits while using less chemical inputs and for society as agriculture makes another step towards becoming more circular.

Supplementary material

Supplementary material is available online at: https://doi.org/10.6084/m9.figshare.26303233

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Conflict of interest

The authors have no conflict of interest to declare.

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Appendices

A Pests, diseases, insecticides & fungicides addressed in this research

TABLE A1 Pests and diseases of common in *Brassica* production. The table details the pests and diseases addressed and accounted for in this research

Order	Common name of pest	Scientific name
Lepidoptera	White butterfly – large	*Pieris brassicae*
	White butterfly – small	*Pieris rapae*
	Diamond-back moth	*Plutella xylostella*
	Garden pebble moth	*Evergestis forficalis*
	Cutworm – turnip moth	*Agrotis segetum*
	Cabbage moth	*Mamestra brassicae*
	Silver Y moth	*Autographa gamma*
Diptera	Cabbage root fly	*Delia radicum*
Coleoptera	Flea beetles	Phyllotreta species
Hemiptera	Potato aphid	*Macrosiphum euphorbiae*
	Cabbage aphid	*Brevicoryne brassicae*
	Peach-potato aphid	*Myzus persicae*
	Cabbage whitefly	*Aleyrodes proletella*
Thysanoptera	Thrips	*Thrips tabaci*
Kingdom	Common name of disease	Scientific name
Fungi	Wirestem	*Rhizoctonia solani*
	Ringspot	*Mycosphaerella brassicicola*
	Phoma leaf spot/Canker	*Phoma lingham*
	Dark leaf spot	*Alternaria brassicae* and *Alternaria brassicicola*
	Powdery mildew	*Erysiphe cruciferarum*
	Light leaf spot	*Pyrenopeziza brassicae*
Bacteria	Spear rot	*Pseudomonas species*
	Xanthomonas black rot	*Xanthomonas campestris pv. campestris*
SAR[a]	Downy mildew	*Hyaloperonospora brassicae*
	White blister (white rust)	*Albugo candida*
	Clubroot	*Plasmodiophora brassicae*

[a] SAR = stramenopiles, alveolates, and Rhizaria.

TABLE A2 Overview of pests and diseases, pesticides and active ingredients. This table details the insecticides and fungicides addressed and accounted for in this research. More specifically, the table overviews the active ingredients in the products (column 1), the commercial names of the products (column 2) and which pests or diseases addressed in this research are targeted by the product (column 3)

Active chemical ingredient	Chemical insecticides	Pests
deltamethrin 25	Desect Spray	Phyllotreta species
	Luxan Delete	*Brevicoryne brassicae*
	Luxan Delete Spray	*Macrosiphum*
	Desect	*euphorbiae*

TABLE A2 (Continued)

Active chemical ingredient	Chemical insecticides	Pests
	Omni Insect	*Myzus persicae*
	–	
	Decis Protech	–
	Decis	*Autographa gamma*
	Imex-Deltamethrin E.C. 25	*Pieris brassicae*
		Pieris rapae
		Evergestis forficalis
chlorantraniliprole (200)	APN chlorantraniliprole	*Mamestra brassicae*
	200 SC	*Pieris brassicae*
	CORAGEN	*Pieris rapae*
	VOLIAM	*Evergestis forficalis*
	WOPRO Insect-weg	*Plutella xylostella*
spirotetramat 150	Batavia	*Aleyrodes proletella*
	MOVENTO	*Brevicoryne brassicae*
indoxacarb	STEWARD	*Mamestra brassicae*
		Pieris brassicae
		Pieris rapae
		Evergestis forficalis
		Plutella xylostella
lambda-cyhalothrin 100	Insect Plus	*Aleyrodes proletella*
	Insect Plus Concentraat	*Brevicoryne brassicae*
	Insect-Ex Concentraat	*Macrosiphum*
	Insect-Ex Kant en Klaar	*euphorbiae*
	Karate Garden	*Myzus persicae*
	Karate Garden Spray	*Thrips tabaci*
	–	
	GOLDORAK	–
	Karate Zeon	*Pieris brassicae*
	Ninja	*Pieris rapae*
		Plutella xylostella
		Thrips tabaci
spinosad 480	TRACER	*Mamestra brassicae*
		Pieris rapae
		Plutella xylostella
esfenvaleraat 25	Sumi-Alpha 2.5 EC	*Mamestra brassicae*
	Sumicidin Super	*Pieris brassicae*
		Pieris rapae
		Plutella xylostella

TABLE A2 (Continued)

Active chemical ingredient	Chemical fungicides	Diseases
azoxystrobin 200/difenoconazool 125	Amistar Top	*Alternaria brassicae*
		Alternaria brassicicola
		Mycosphaerella brassicicola
		Albugo candida
		Erysiphe cruciferarum
azoxystrobin 250	Dynasty	*Phoma lingham*
		Pyrenopeziza brassicae
		Rhizoctonia solani
		Alternaria brassicae
		Alternaria brassicicola
		Mycosphaerella brassicicola
		Albugo candida
	–	*Erysiphe cruciferarum*
	Ortiva	–
	Amiplus Azoxystrobin	*Alternaria brassicae*
	Amistar	*Alternaria brassicicola*
	Globaztar AZT 250 SC	*Mycosphaerella*
	Mirador	*brassicicola*
	Profi AZ 250 SC	*Albugo candida*
	Zakeo 250 SC	*Erysiphe cruciferarum*
fluopicolide 63, propamocarb 524	Infinito Matix	*Albugo candida*
prothioconazool 480	Rudis	*Mycosphaerella brassicicola*

B Fixed parameters

TABLE B1 Fixed parameters used in the baseline scenario of the partial budget

	Variable	Measure/parameter
Broccoli		
	Plants planted per hectare (for conventional and organic production)	38,000
	Conventional yield (plants/hectare)	30,400
	Organic yield (kg/hectare)	7,500
	Insecticides – Dose (in l/hectare unless specified otherwise)	
	Chlorantraniliprole (200)	0.13
	Deltamethrin (25)	0.30(×2 applications)
	Indoxacarb (kg/hectare)	0.25
	Fungicides – Dose (l/hectare)	
	Azoxystrobin (200)/Difenoconazool (125)	1.00
Brussels sprouts		
	Plants planted per hectare (for conventional and organic production)	33,300
	Conventional yield (kg/hectare)	25,000
	Organic yield (kg/hectare)	9,000
	Insecticides – Dose (l/hectare)	
	Spinosad (480)	0.40
	Spirotetramat (150)	1.00
	Lambda-Cyhalothrin (100)	0.15
	Esfenvaleraat (25)	0.40
	Fungicides – Dose (l/hectare)	
	Fluopicolide (63), Propamocarb (524)	0.75
	Azoxystrobin (250)	2.00
	Prothioconazool (480)	1.20
Financial input		
	Conventional Broccoli sale price (euro/head)	0.50
	Organic Broccoli sale price (euro/kg)	1.25
	Conventional Brussels Sprouts sale price (euro/kg)	0.40
	Organic Brussels Sprouts sale price (euro/kg)	1.50
	Conventional Broccoli net profit (euro/hectare)	12,551
	Organic Broccoli net profit (euro/hectare)	6,086
	Conventional Brussels Sprouts net profit (euro/hectare)	5,658
	Organic Brussels Sprouts net profit (euro/hectare)	10,528
	Price of (in euro/l unless specified otherwise)	
	Chlorantraniliprole (200)	380.00
	Deltamethrin (25)	36.50
	Spinosad (480)	430.00
	Spirotetramat (150)	130.00
	Indoxacarb (euro/kg)	320.00
	Lambda-Cyhalothrin (100)	123.00
	Esfenaleraat (25)	34.00
	Fluopicolide (63), Propamocarb (524)	19.50
	Azoxystrobin (250)	43.00
	Prothioconazole 480)	146.00
	Azoxystrobin (200)/Difenoconazole (125)	72.00

Note: All parameters are from KWIN-AGV 2018 (sections 6.3.9, 6.3.14, 7.3.4 and 7.3.7).

C Insect frass experts' expectations for frass' performance in reducing pests and diseases

Table C1 provides three estimates per year: average lowest estimate, average most likely estimate, average highest estimate. The estimates in the table are listed as percentages. For example, 0.05 translates to a 5% reduction of the pest or disease.

A negative value means that the presence of the pest or disease is expected to increase when applying insect frass. A positive value means that the presence will decrease the presence of the pest or disease.

Experts voluntarily provided estimations. As such, not all experts were comfortable providing estimations for all pests and diseases. The column "nr. of experts" specifies how many of the six experts provided estimations for the given pest or disease.

In addition to the quantitative estimates, experts also explained their reasoning. A key consideration during the discussion on pests was regarding which of the plant's phy-

TABLE C1 Expected reduction in pest and disease presence when applying insect frass compared to no frass application

Pests	Nr. of experts	Year 0	Year 4	Year 8
Lepidoptera				
Pieris brassicae	3	−0.01, 0.05, 0.11	0.00, 0.08, 0.17	0.02, 0.10, 0.18
Pieris rapae	3	−0.01, 0.05, 0.11	0.00, 0.08, 0.17	0.02, 0.10, 0.18
Plutella xylostella	5	0.04, 0.07, 0.12	0.06, 0.12, 0.18	0.08, 0.14, 0.20
Mamestra brassicae	2	0.04, 0.08, 0.11	0.05, 0.13, 0.20	0.08, 0.15, 0.23
Evergestis forficalis	1	0.10, 0.15, 0.20	0.10, 0.20, 0.30	0.10, 0.20, 0.30
Agrotis segetum	1	0.10, 0.15, 0.20	0.10, 0.20, 0.30	0.10, 0.20, 0.30
Autographa gamma	1	0.10, 0.15, 0.20	0.10, 0.20, 0.30	0.10, 0.20, 0.30
Hemiptera				
Macrosiphum euphorbiae	3	−0.02, 0.04, 0.10	0.03, 0.09, 0.15	0.07, 0.16, 0.20
Brevicoryne brassicae	6	0.02, 0.06, 0.12	0.05, 0.10, 0.15	0.07, 0.15, 0.19
Myzus persicae	4	0.00, 0.05, 0.11	0.03, 0.09, 0.15	0.07, 0.16, 0.19
Aleyrodes proletella	2	0.05, 0.13, 0.20	0.13, 0.15, 0.20	0.18, 0.23, 0.28
Other				
Delia radicum	6	0.07, 0.13, 0.19	0.10, 0.16, 0.23	0.10, 0.16, 0.23
Phyllotreta sp.	4	−0.04, 0.00, 0.05	−0.03, 0.02, 0.07	−0.03, 0.02, 0.07
Thrips tabaci	6	0.03, 0.07, 0.13	0.05, 0.11, 0.16	0.07, 0.13, 0.18

Diseases	Nr. of experts	Year 0	Year 4	Year 8
Fungi				
Rhizoctonia solani	3	0.03, 0.18, 0.28	0.06, 0.23, 0.33	0.08, 0.24, 0.34
Phoma lingham	3	0.00, 0.17, 0.27	0.03, 0.22, 0.33	0.03, 0.23, 0.33
Alternaria brassicae and *Alternaria brassicicola*	2	−0.05, 0.18, 0.30	−0.05, 0.20, 0.35	−0.03, 0.20, 0.35
Mycosphaerella brassicicola	1	0.10, 0.15, 0.20	0.10, 0.20, 0.30	0.15, 0.20, 0.30
Erysiphe cruciferarum	1	0.10, 0.15, 0.20	0.10, 0.20, 0.30	0.15, 0.20, 0.30
Pyrenopeziza brassicae	1	0.10, 0.15, 0.20	0.10, 0.20, 0.30	0.15, 0.20, 0.30
Bacteria				
Pseudomonas sp.	4	0.03, 0.11, 0.18	0.05, 0.15, 0.23	0.08, 0.16, 0.23
Xanthomonas campestris pv. campestris	4	0.03, 0.11, 0.18	0.05, 0.15, 0.23	0.08, 0.16, 0.23
SAR[a]				
Hyaloperonospora brassicae	2	0.05, 0.10, 0.20	0.10, 0.18, 0.20	0.15, 0.20, 0.25
Albugo candida	2	0.10, 0.13, 0.20	0.13, 0.18, 0.23	0.18, 0.20, 0.28
Plasmodiophora brassicae	4	0.05, 0.09, 0.15	0.06, 0.11, 0.19	0.06, 0.11, 0.19

[a] SAR = stramenopiles, alveolates, and Rhizaria is a formal taxon clade.

tohormonal pathways the pest induces when it feeds on the plant. When the pest feeds on the plant, the plant responds with induced defense that involves the activation of gene expression. In brief, induced gene expression can initiate a direct defense against the pest by triggering the synthesis of defense-related proteins or secondary plant metabolites. Indirectly, it can modify the blend of volatile organic compounds released by the plant, which attracts natural enemies of the pest (Stam *et al*., 2014). The consensus was that because the mechanism underlying frass' activity involving the stimulation of plant growth-promoting rhizobacteria requires an active jasmonic acid response, then especially jasmonic acid inducing pests would be affected by frass-mediated resistance (Barragán-Fonseca *et al*., 2022). Jasmonic acid inducing pests discussed in this research include: flea beetles, thrips, cabbage root flies, and the lepidopteran caterpillars.

Table B2 gives more insight into specific viewpoints.

Note, in Figure C1, only pests and diseases with estimations provided by three or more experts are included. The following pests and diseases were omitted from Figure C1 but can be found in Tables C1 and C2: *Aleyrodes proletella* (cabbage white fly), *Autographa gamma* (silver Y moth), *Mamestra brassicae* (cabbage moth), *Agrotis segetum* (cutworm – turnip moth), *Evergestis forficalis* (garden pebble moth), *Mycosphaerella brassicicola* (ringspot), *Alternaria brassicae* and *Alternaria brassicicola* (dark leaf spot), *Erysiphe cruciferarum* (powdery mildew), *Pyrenopeziza brassicae* (light leaf spot), *Hyaloperonospora brassicae* (downy mildew) and *Albugo candida* (white blister/rust).

TABLE C2 Justifications for frass performance estimations regarding pests and disease

Take home message – pests	Discussion points
Flea beetles are not expected to be affected by frass.	Based on one year of monitoring field research, there was no significant difference in beetle performance except for on a few frass-treated plants where it was a slightly decreased.
Frass is expected to cause a slight reduction of the presence of thrips.	During an accidental thrips infestation, thrips were appearing first on the control plants and later on the frass-treated plants. This may be because thrips induces mainly jasmonic acid pathways.
Frass is not expected to change the populations of Lepidopteran and aphids in the short-term but are expected to be reduced long-term.	In the first year, the parasitization will not be that effective yet because a stable population of parasitoids is needed. As an example, what was seen in recent field experiments was that the aphids and *Plutella* were more present on the frass-treated plants at first; then the recruitment of parasitoids increased on frass-treated plants. Such parasitoid recruitment is expected to be stronger over time. Therefore, in the first year, a positive effect of frass on aphid and Lepidopteran presence is not expected (maybe there is even an increase), but in later years, the parasitoid population is expected to be better established.
The cabbage root fly is not expected to be affected by frass over the long-term.	The bacterial composition or microbiome reverts back between 8 and 16 weeks; it does not buildup over the years. Therefore, it is not expected that the beneficial microbes against *Delia radicum* are stimulated long-term. Also, Delia has quite a dispersive range (for kilometers). If *Brassica* crops are located in the region over consecutive years, a resident population could be continuously present and fluctuating over time. Because of this, it matters less what the farmer is doing on other parts of his field (e.g. establishing parasitoid populations), and it matters more what is taking place throughout the whole province. Therefore, a reduction of the Delia population is not expected overtime.

Take home message – diseases	Discussion points
Frass will reduce soil-borne diseases more than leaf-borne diseases.	The distinction between soil-borne and leaf-infectious diseases is important. With soil-borne pathogens, there can be direct interactions with the microbes. The effects of the frass are expected to serve as a biocontrol by creating interference of the recruited microbiome directly on the soil-borne pathogens. Soil-borne fungal diseases have chitin in their cell walls, so it is assumed then that this enrichment of chitin degrading microorganisms following the addition of insect frass can have an effect on reducing the population, particularly for Rhizoctonia. With leaf-borne pathogens, the effects are more indirect and relate to induced systemic resistance of the plant.
Frass is expected to reduce the presence of *Pseudomonas* and *Xanthomonas*.	*Pseudomonas* and *Xanthomonas* are gammaproteobacteria, which is a group of microbes that were found to be stimulated during early stage of decomposition that happens in insect exuviae or frass. It raises questions whether these bacteria (that causes spear rot or black rot) may also exist while the microbes are stimulated; thus far, it is unknown. Granted, the presence of gammaproteobacteria is temporary; after about four weeks they are gradually replaced by an increasing presence of bacillus – believed to play a major role during this biocontrol of diseases in the soil. The bacilli would eventually destroy the gammaproteobacteria in approximately eight to sixteen weeks.

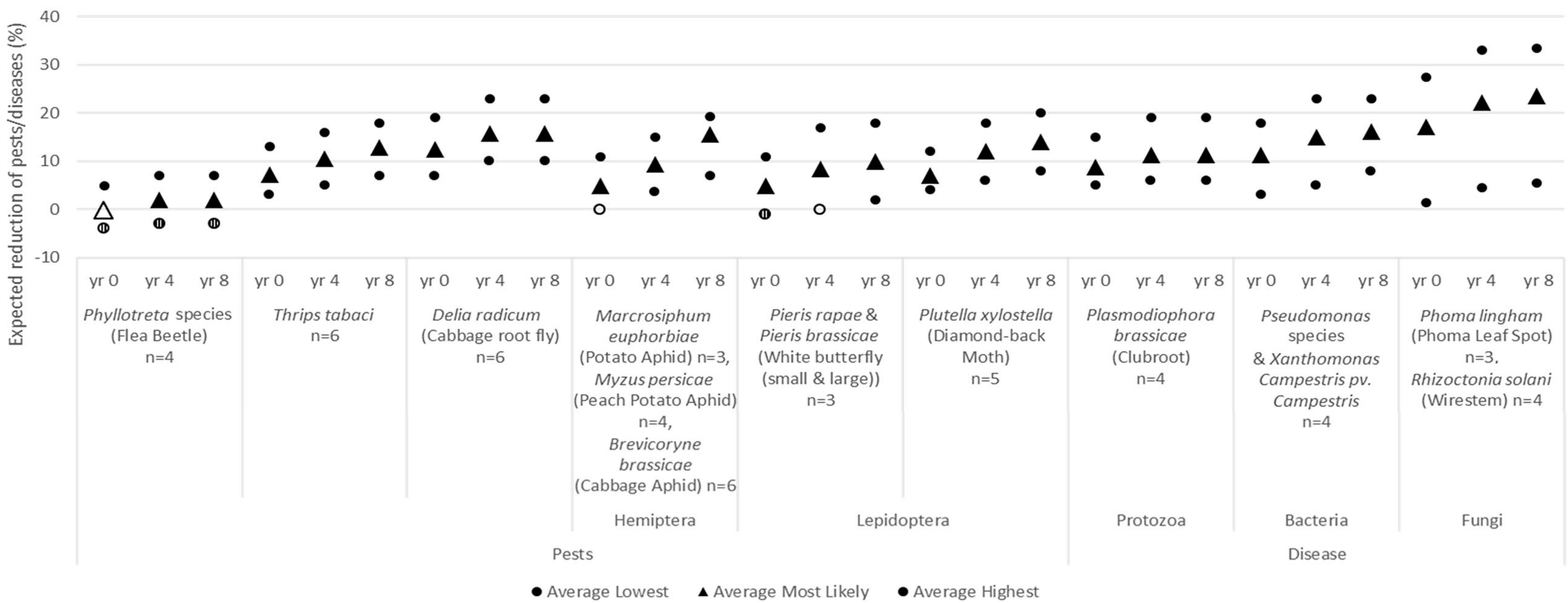

FIGURE C1 Expected reduction of pests and diseases common in *Brassica* production when applying insect frass compared to no frass application based on elicitation with frass experts. In the graph, circles represent the averaged upper and lower bounds of the estimates; triangles represent the averaged most likely estimates. A transparent shape fill occurs at 0%, which indicates that frass is not expected to increase nor decrease the pest or disease presence. A negative percentage (noted with vertical line fill) indicates that frass is expected to increase the quantity of the pest or disease presence. Below each category on the *x*-axis an "n" is specified, which indicates how many experts were willing and able to provide an estimation.

D Estimations of frass' influence on insecticide & fungicide use & qualitative explanation

In addition to the quantitative estimates, experts also explained their reasoning. The use of insecticides and fungicides in organic and conventional broccoli production was expected to be reduced more than in Brussels sprouts production (with the exception of Deltamethrin (25) in conventional broccoli production). The crop advisors emphasized, if frass were able to delay the development of pests or diseases, it would have the most potential to reduce the use of pesticides in broccoli than in Brussels sprouts because broccoli spends less time on the field and therefore has less chance of infestation or infection. Therefore, the chance that frass can delay the onset of pests and diseases in broccoli long enough to reduce the need for future pesticide treatments is greater than for Brussels sprouts.

TABLE D1 Stochastic parameters used to model the net profit of applying insect frass as a crop and soil health promoter

Parameter		PERT distribution parameters[a]		
		Year 0	Year 4	Year 8
Broccoli				
Insecticides				
Dose reduction (%):				
	Chlorantraniliprole (200)	−0.05, 0.10, 0.25	0.08, 0.23, 0.38	0.20, 0.40, 0.60
	Deltamethrin (25)	−0.05, 0.00, 0.05	0.00, 0.05, 0.10	0.00, 0.10, 0.20
	Indoxacarb	−0.05, 0.10, 0.25	0.08, 0.23, 0.38	0.20, 0.40, 0.60
Insecticides used in organic production				
Dose reduction (%):				
	Bacillus thuringiensis	0.00, 0.10, 0.30	0.10, 0.30, 0.50	0.30, 0.50, 0.70
	Tracer (spinosad)	0.00, 0.10, 0.20	0.10, 0.20, 0.30	0.25, 0.35, 0.45
Fungicides				
Dose reduction (%):				
	Azoxystrobin (200)/Difenoconazool (125)	−0.05, 0.10, 0.25	0.08, 0.23, 0.38	0.20, 0.40, 0.60
Brussel sprouts				
Insecticides				
Dose reduction (%):				
	Spinosad (480)	−0.05, 0.03, 0.13	0.00, 0.10, 0.25	−0.03, 0.18, 0.38
	Spirotetramat (150)	−0.05, 0.03, 0.13	−0.03, 0.05, 0.20	−0.05, 0.10, 0.30
	Lambda-Cyhalothrin (100)	−0.05, 0.03, 0.13	0.00, 0.10, 0.25	−0.03, 0.18, 0.38
	Esfenvaleraat (25)	−0.05, 0.03, 0.13	0.00, 0.10, 0.25	−0.03, 0.18, 0.38
Insecticides used in organic production				
Dose reduction (%):				
Bacillus thuringiensis	0.00, 0.05, 0.10	0.05, 0.10, 0.15	0.10, 0.15, 0.20	
	Tracer (spinosad)	0.00, 0.03, 0.05	0.00, 0.03, 0.05	0.00, 0.03, 0.05
Fungicides				
Dose reduction (%):				
	Fluopicolide (63), Propamocarb (524)	−0.03, 0.05, 0.13	−0.03, 0.13, 0.28	0.00, 0.20, 0.40
	Azoxystrobin (250)	−0.03, 0.05, 0.13	−0.03, 0.13, 0.28	0.00, 0.20, 0.40
	Prothioconazool (480)	−0.03, 0.05, 0.13	−0.03, 0.13, 0.28	−0.03, 0.18, 0.38

[a]Key = minimum, most likely, maximum.
The error bars indicate the net change in profit at 90% certainty. The estimates in the table are listed as percentages. For example, 0.05 translates to a 5% reduction of the insecticide or fungicide.

TABLE D2 Justifications for frass performance estimations regarding insecticides and fungicides

Take home message – insecticides	Discussion points
Conventional insecticides	The effects in the first year of use will be less than subsequent years because the bacteria must perform several processes before the chitin is usable, and the resilience in the soil requires years to build-up with subsequent applications. If the farmer (especially considering those in conventional systems) only applies pesticides based on a schedule and not based on monitoring, frass is not going to be an effective product. The farmer must be willing to monitor the crop and apply crop protection based on what they see and what they expect to take place.
Organic insecticides	There are few insecticides used in organic broccoli. For instance, Tracer might be used, but it is not a selective insecticide. If farmers use the frass for several years, the Tracer application could be removed in broccoli production. Because organic Brussels sprouts are so difficult to grow, the small amount of Tracer that the farmers may be using cannot be reduced.

Take home message – fungicides	Discussion points
Conventional fungicides	Not many fungicides are used in conventional broccoli. A reduction in fungicides would be expected most for those targeting soilborne diseases, but this will take time, as resilience is built up in the soil overtime; that does not happen in one year. Chitin can stimulate the soil life in a way that makes the plant stronger against fungi.
More effect is expected in reducing fungicides than insecticides	Frass can be applied to the soil where it can directly affect soil-borne diseases. For diseases like *Albugo candida*, if you had a field with crop residue with the fungi living on it, then the resilience built up in the soil from the frass will make the next proximal parcel of land less susceptible to it.
No fungicides are used in organic broccoli nor Brussels sprouts production.	

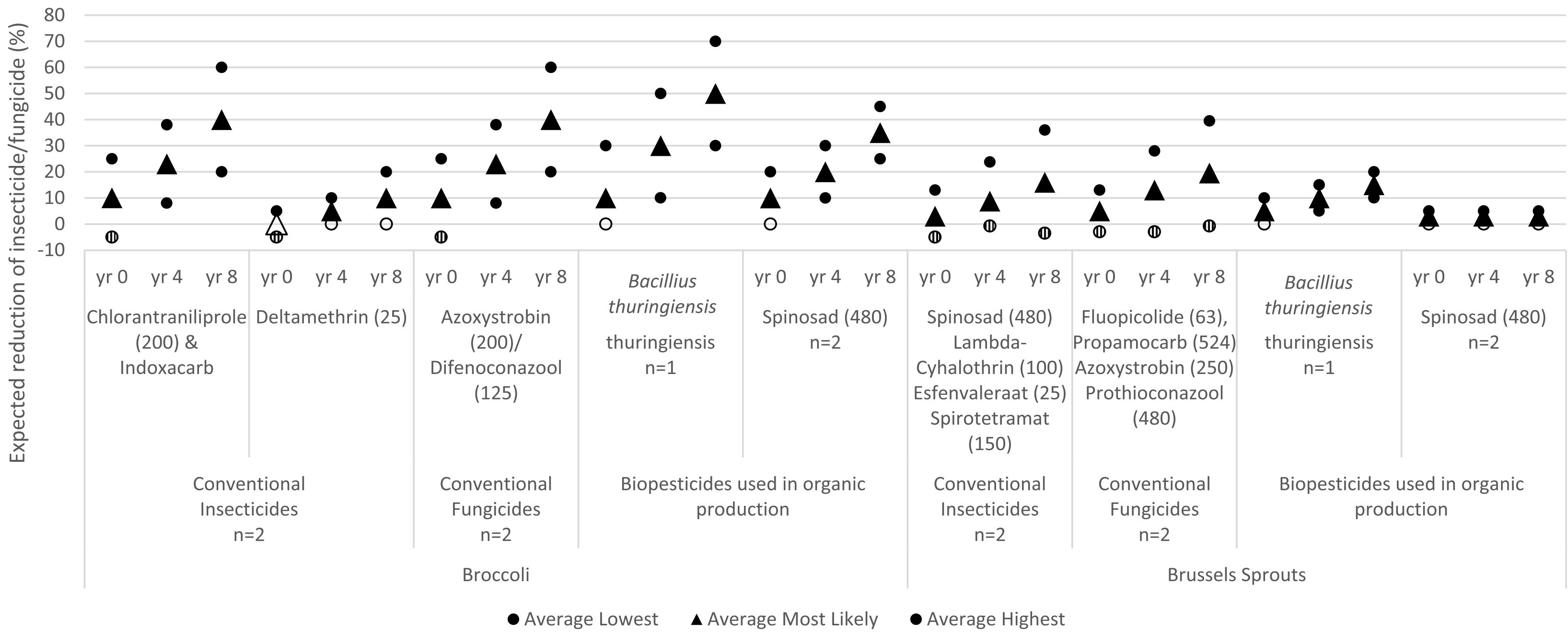

FIGURE D1 Expected change in insecticide and fungicide applications for *Brassica* production when applying insect frass compared to no frass application based on interviews with crop advisors. In the graph, circles represent the averaged upper and lower bounds of the estimates; triangles represent the averaged most likely estimates. A transparent shape fill occurs at 0%, which indicates that frass is not expected to increase nor decrease the quantity of the insecticide or fungicide applied. A negative percentage (noted with vertical line fill) indicates that frass is expected to increase the quantity of insecticide or fungicide applied. Below each category on the *x*-axis an "n" is specified, which indicates how many experts were willing and able to provide an estimation.

E Estimations of frass' influence on crop yield & qualitative explanation

Table E1 provides three estimates per year: average lowest estimate, average most likely estimate, average highest estimate. The estimates in the table are listed as percentages. For example, 0.05 translates to a 5% increase in yield.

A positive value means that the crop yield is expected to increase with the application of frass.

Experts voluntarily provided estimations. Notably all six frass experts and all three crop advisors provided estimations for frass' expected effects on crop yield (noted in the column "nr. of experts").

In addition to the quantitative estimates, experts also explained their reasoning. The frass experts discussed yield in terms of organic versus conventional production and estimated the yield to most likely improve by between 8-13% in either system. The crop advisors posited that frass would improve conventional broccoli yield more than conventional Brussels sprouts because, compared to broccoli, Brussels sprouts is a more challenging crop in terms of its susceptibility to pests and diseases. In addition, crop loss in broccoli can be severe if caterpillars infest and occupy the flowers of the broccoli; their presence deems the broccoli an unconsumable end product, which cannot be sold. If frass can build up the soil's resilience and therefore the plant's natural protection against caterpillars, it can reduce the chance of broccoli loss from caterpillars. Regarding organic yield, crop advisors expected that Brussels sprouts could experience more improved yields than broccoli. As there are few products allowed to be used in organic Brussels sprouts production, there is a lot of potential gain for frass to reduce the amount of crop loss.

TABLE E1 Expected increase in *Brassica* production yield when applying insect frass compared to no frass application

	Nr. of experts	Year 0	Year 4	Year 8
Frass experts				
Conventional Production	6	0.01, 0.08, 0.14	0.03, 0.10, 0.17	0.04, 0.13, 0.18
Organic Production	6	0.03, 0.09, 0.15	0.06, 0.12, 0.18	0.05, 0.13, 0.18
Crop advisors				
Conventional broccoli	3	0.00, 0.06, 0.13	0.03, 0.14, 0.25	0.05, 0.16, 0.28
Organic broccoli	3	0.00, 0.04, 0.08	0.05, 0.13, 0.20	0.05, 0.13, 0.20
Conventional Brussels sprouts	3	0.00, 0.03, 0.07	0.00, 0.06, 0.12	0.00, 0.06, 0.12
Organic Brussels sprouts	3	0.00, 0.03, 0.06	0.03, 0.11, 0.18	0.00, 0.13, 0.25

TABLE E2 Justifications for frass performance estimations regarding yield

Take home message	Discussion points
Frass will improve organic yields more than conventional.	*Frass experts*: Organic farmers are more ready to reap the potential benefits of insect frass in the first year(s), especially for those who already depend on and have biological control agents (e.g. microbes or insects) present in the fields.
	Crop advisors: There is more crop loss in organic than conventional production. With the frass stimulating the bacteria life, potentially less of the organic yield is lost.
Frass will improve conventional yields more than organic.	*Frass experts*: On conventional fields, more pathogens and pests are completely eradicated in the previous season because of pesticide use. Therefore, from the beginning of each year, conventional farms have the advantage of less pest and disease pressure to cope with.
	Frass experts: In conventional production, it is assumed that there is lower bacterial diversity and a lower biocontrol agent availability because of their use of pesticides. Therefore, in earlier years, insect frass will not be as effective on conventional farms (compared to on organic farms), but there is a steeper increased effectiveness overtime for conventional farms as they become more dependent on biological control agents and reap more benefits from insect frass.
	Crop advisors: In organic production, the producers are already increasing the soil life and resilience in other ways. The extra effects that are prompted by frass will therefore be less in organic production.
Frass will only slightly improve conventional yields.	*Frass experts*: Conventional farm fertilization is already quite optimal, and they achieve high yields; there is no shortness in fertilizer. Though insect frass contains nutritional elements, its main purpose is for better controlling diseases and pests by building up a community of microbes in the soil over time.
	Crop advisors: Conventional production is already very optimal. Potential conventional yield increases more than 5% would be difficult to achieve.
Frass will improve conventional broccoli yield more than Brussels sprouts.	*Crop advisors*: A lot of the end product that is lost is because there are caterpillars hiding in it and then it is not a consumable product. The losses can be severe.
	Crop advisors: In broccoli, if chitin will stimulate and create more bacteria life and in doing so creates more activity in the soil and better mineral uptake by the plant, then the plant develops a better root system and can grow steadier and more efficiently.
Frass will improve organic Brussels sprouts yield more than broccoli.	*Crop advisors*: Organic Brussels sprouts yield will be more than the yield in broccoli because the growers must throw away a lot more end product due to its quality. There is a lot of room for improvement for reducing crop loss especially when the bacilli are optimal and can make the plant grow well and in balance.

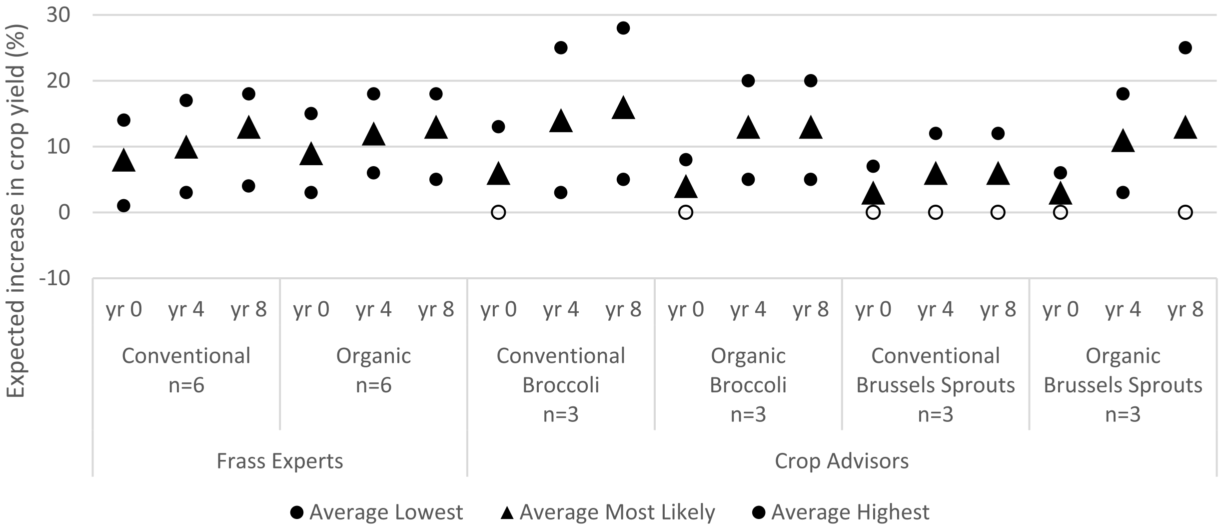

FIGURE E1 Expected increase in *Brassica* crop yield when applying insect frass compared to no frass application based on elicitation with frass experts and interviews with crop advisors. In the graph, circles represent the averaged upper and lower bounds of the estimates; triangles represent the averaged most likely estimates. A transparent shape fill occurs at 0%, which indicates that frass is not expected to increase nor decrease crop yield. No negative percentages were found. Below each category on the x-axis an "n" is specified, which indicates how many experts were willing and able to provide an estimation.

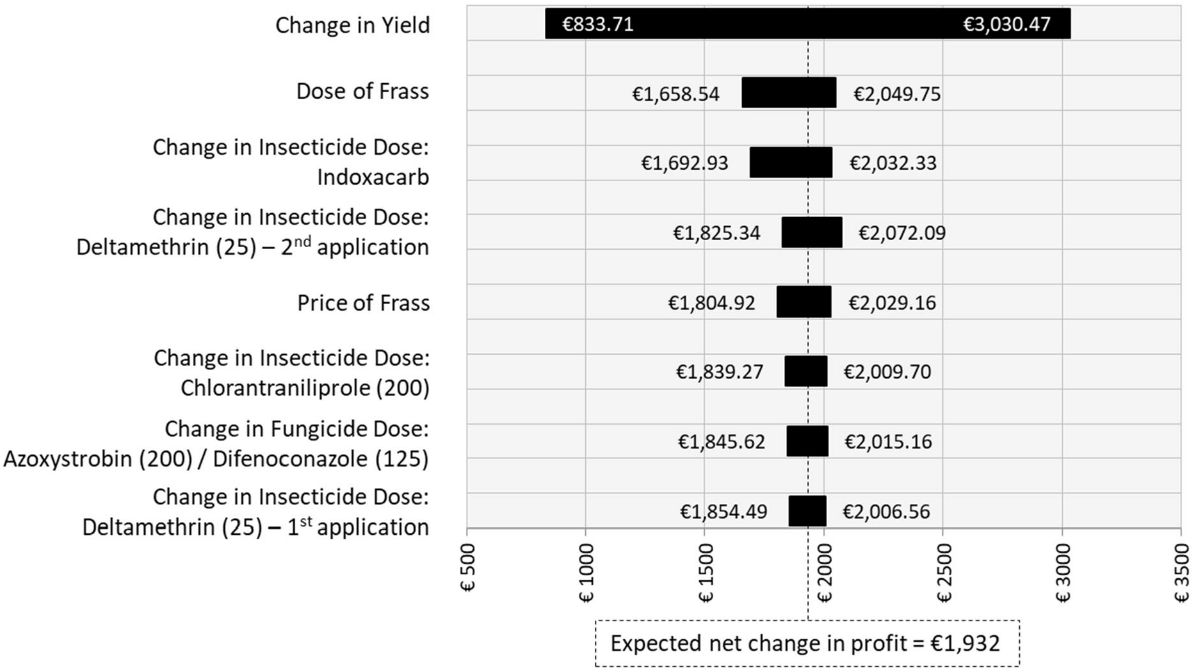

FIGURE F1 Example net change in profit input sensitivity (tornado) graph – conventional broccoli (year 4).

F Example sensitivity analysis for conventional broccoli (year 4)

Figure F1 shows a tornado graph of conventional broccoli production in year 4 as an example to illustrate the net change in profit's sensitivity to yield. The graph shows to which input variables the uncertainty behind the expected net change in profit can be attributed to. In this example, the expected net change in profit for conventional broccoli (year 4) is €1,932. The *x*-axis likewise is a scale for the sensitivity of the expected net change in profit. Each stochastic input that was inserted in the model appears on the *y*-axis. Next to each input is a horizontal bar of varying lengths. The bar indicates how much the expected net change in profit can differ, holding all other inputs constant and varying the one input only. The longer the bar, the more uncertainty it brings into the calculation of the expected net change in profit.

The inputs on the *y*-axis are ordered from having the most to the least influence on the expected net change in profit. All the tornado graphs generated for each type of production indicated that the change in yield attributes the most uncertainty to the expected net change in profit.