Decision Support for determining effective climate measures in banana production

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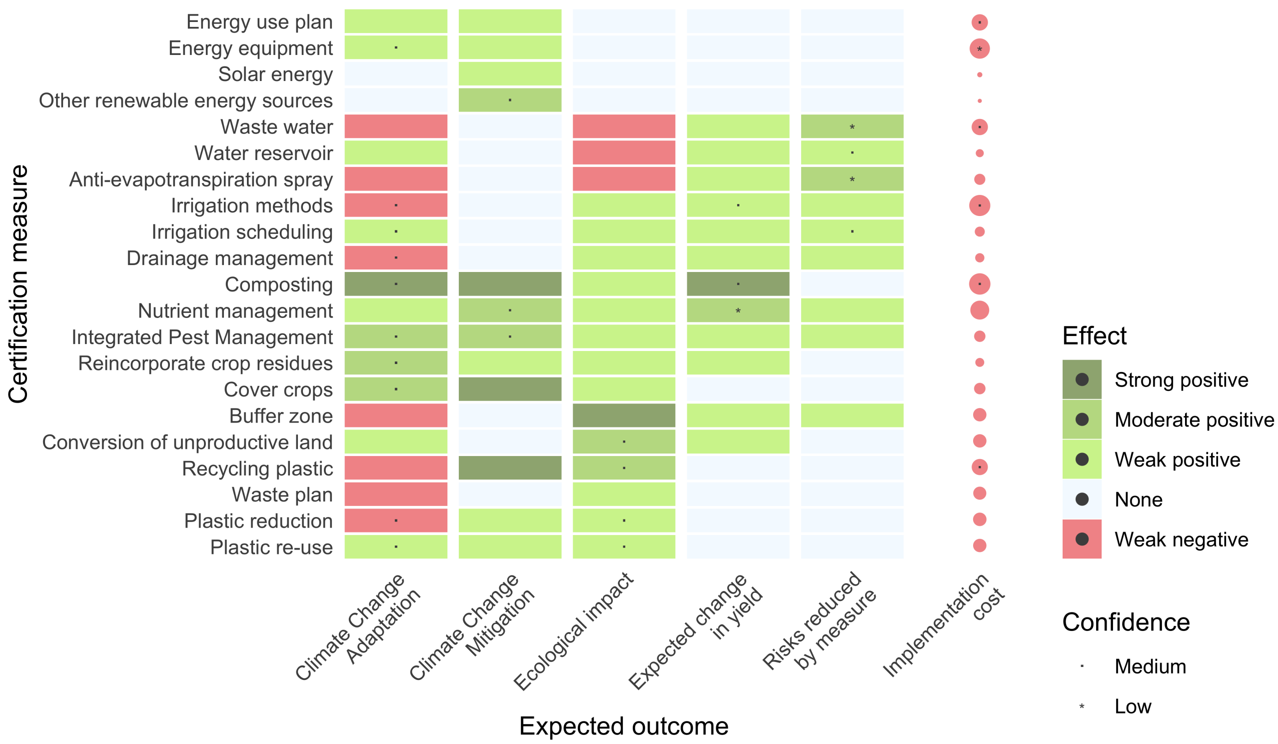
Executive summary

To support the Action Alliance for Sustainable Bananas (ABNB) in the field of climate change adaptation and mitigation in the banana sector we gathered expert knowledge and literature findings and used them to generate a simulation of the expected impacts of certification measures. We offer an evaluation of which mitigation and adaptation measures are most effective. A prioritized list of measures is presented. The results are specific to high rainfall export oriented banana production regions of Latin America.

According to our simulation the certification measures that were most effective in terms of adaptation to climate change impacts were cover crops, composting, reincorporation of crop residues and integrated pest management (IPM). To estimate adaptation effects we quantified the total benefits of the measures and compared those with the costs required to implement them.

To estimate climate change mitigation impacts we quantified the effects of the measures on global greenhouse gas emissions. Those measures that promised the most favorable climate change mitigation outcomes were composting, cover crops and recycling plastic.

We also simulated the ecological impacts of the measures and found that buffer zones, conversion of unproductive land and recycling plastics had the greatest positive effect. To estimate the ecological impacts we quantified the effects of the measure on surrounding biodiversity and habitats.



Effect	Climate Change Adaptation	Climate Change Mitigation	Ecological impact	Expected change in yield	Risks reduced by measure
Strong positive	> 55%	> 50%	> 50%	> 20%	> 15%
Moderate positive	30 to 55%	25 to 50%	25 to 50%	10 to 20%	8 to 15%
Weak positive	0 to 30%	0 to 25%	0 to 25%	0 to 10%	0 to 8%
None	0%	0%	0%	0%	0%
Weak negative	< 0%	< 0%	< 0%	< 0%	< 0%

Figure 1: Qualitative differences between farms with and without certification measures. We classified the expected effect according to the thresholds shown in the table. These thresholds represent the median of 10,000 simulations of the expected change with the certification measure. We describe the confidence in our assignment of outcomes to these classes according to the percentage of the total simulations that fell in the same class.

Introduction

The Action Alliance for Sustainable Bananas (ABNB) pledged to intensify its activities in the field of climate change adaptation and mitigation in the banana sector. This document outlines an attempt to support this effort by gathering and applying the knowledge of experts in the field of climate change adaptation and mitigation in banana production systems. Their knowledge is applied in order to evaluate, which mitigation and adaptation measures – that are currently available to most farmers – are most impactful, cost-effective and pose the lowest risks. The goal is to provide a prioritized list of certification measures, which should guide not only plantation owners and farmers but also certification schemes. The work is focused on the main exporter banana production systems in Latin America. The results are specific to these high rainfall export oriented banana production regions.

Methodology

Many of the variables decision makers need to consider in development cannot be precisely quantified, at least not without unreasonable effort. The major objective of (prescriptive) decision analysis is to support decision-making processes that are faced with this problem (Luedeling and Shepherd 2016). Decision analysis uses expert knowledge and stochastic models to generate forecasts of decision outcomes without requiring precise numbers.

The `decisionSupport` package (Luedeling, Goehring, and Schiffers 2020) implements this in the R programming language (R Core Team 2020) as a Monte Carlo simulation, which generates a large number of plausible system outcomes, based on random numbers for each input variable, drawn from user-specified probability distributions. This process requires two inputs:

1) an R function that predicts decision outcomes based on the variables named in a separate data table. This R function specifies a decision model that is customized by the user to address a particular decision problem.
2) an input table (in .csv format) specifying the names and probability distributions for all variables used in the decision model. These distributions aim to represent the full range of possible values for each component of the model.

These two inputs are provided as arguments to the `mcSimulation()` function, which conducts a Monte Carlo analysis with repeated model runs based on probability distributions for all uncertain variables. The data table and model are customized to fit the particulars of a specific decision.

We apply `decisionSupport` together with `tidyverse` libraries (Wickham et al. 2019) including `ggplot2` (Wickham, Chang, et al. 2020), `plyr` (Wickham 2020) and `dplyr` (Wickham, François, et al. 2020) among others in the R programming language (R Core Team 2020) to generate a decision model as a simulation function cf. decision simulations regarding water management in Burkina Faso (Lanzanova et al. 2019) and Ethiopia (Yigzaw et al. 2019), horticultural systems in Germany (Ruett, Whitney, and Luedeling 2020), and agroforestry in Uganda (Whitney et al. 2018, 2017) and Vietnam (Do, Luedeling, and Whitney 2020).

We use the `decisionSupport` functions `vv()` to produce time series with variation from a pre-defined mean and coefficient of variation, `chance_event()` to simulate whether events occur and `discount()` to discount values along a time series.

List of defined measures

GIZ provided us with an initial list of several possible climate change mitigation and adaptation relevant certification measures. After consultation with the experts and the literature we defined 20 measures to be assessed. **For each of these the growers/producers/producer groups would be responsible for implementation.** The description of the measure is provided below and our notes about the process of bringing this into the model are listed in *italics*:

1. Energy use plan

Maintaining energy use records (e.g. invoices where energy consumption is detailed). Growers are aware of where and how energy is consumed on the farm and through farming practices. They may also set targets for increasing energy efficiency and for reducing dependency on non-renewable energy sources. The record keeping can help producers to identify measures and make informed decisions on how to reduce energy consumption.

This measures might require additional costs to monitor and plan the energy use for the entire production process.

2. Energy equipment

Use of energy-efficient equipment. Equipment is both selected and maintained for optimum energy consumption.

This measure helps to reduce the energy consumption in the processes where efficient equipment is used that effectively reduces energy costs. The measure also implies the reduction of emissions due to the consumption of energy involved fossil fuel combustion.

3. Renewable energy (including solar and other sources)

Producers consider reducing the use of non-renewable energies to a minimum and use renewable ones. They replace non-renewable sources by renewable ones as far as possible.

In the simulation we consider wind, solar and biomass energy as the main likely sources of renewable energy for banana plantations. We divide this into 3.1 Solar and 3.2 Other (See Adaptation and Mitigation figures). Solar is feasible (cost effective) in some areas of Latin America but not yet in others. However, with the high potential of solar resources and the need for transitioning to renewable energy, solar energy development is promising. Incentives from the government and others, including certification bodies, are needed to support the transformation. The biomass used for energy can be costly and resource intensive (water, soil, synthesized inputs, energy etc.) to produce. On the other hand, organic wastes from banana can be used as source of energy, technologies are needed to make this practicable and cost effective.

4. Waste water

Packing is done daily during harvests and this uses a lot of water which can be used for irrigation requiring an irrigation system to recirculate, reuse and/or recycle water.

In the simulation we assume that this could work only with proper treatment to overcome the risks of salinity, phytotoxicity and other contaminations which can affect banana plants or soil and water ecosystems. Treatment of wastewater incurs costs but increase water availability for irrigation.

5. Water reservoir

Farms make use of water harvesting and rainwater collection where feasible for seasonal water shortages, e.g. from building roofs, glasshouses etc.

In the simulation we assume that the construction of reservoirs is intended to collect rainwater and store water for dry periods. This can help to reduce risks of water shortage for production and at the same time reduce the impact of high rain intensity (i.e. surface runoff and waterlogging) during heavy rain events. The water storage also reduces ground water withdrawal, which may have a positive impact on aquatic ecosystems. The measure can provide both economic and environmental benefits.

6. Anti-evapotranspiration spray

In high rainfall regions the use of organic foliar spray against evapotranspiration may be less effective than in low rainfall regions. Under high rainfall conditions anti-evapotranspiration sprays could suppress banana growth and development. Methods such as mulching and ground cover may also be effective in managing evaporation from the soil surface.

7. Irrigation methods

Apply irrigation methods in order to optimize quantities of water applied.

We consider drip irrigation and under-canopy sprinklers as the main measures applied in this part of the simulation. Irrigation methods that increase irrigation efficiency can have positive economic and ecological impacts.

8. Irrigation scheduling

Schedule the irrigation and have a documented risk assessment that identifies environmental impacts of the water sources, distribution system and irrigation and crop washing usages. They develop and implement a water conservation plan to reduce water use. The plan documents current water consumption, evaluates future water needs and water availability, and establishes targets for improving water use efficiency. Future water needs and water availability are evaluated and targets are set for improving water use efficiency.

In high rainfall regions this may be less relevant, since many of the banana plantations are rainfed. Irrigation may become more relevant in these rain-fed areas in the future and some already face water shortages.

9. Drainage management

Drainage systems for disaster and use suitable techniques (e.g. drainage, subsoiling, permanent row marking, avoiding in-row plowing, smearing, poaching) for use on the land and, where possible, minimize, isolate, or eliminate soil compaction, etc. Soil assessments at least every 3 years. The soil assessment includes erosion prone areas and slope, identification of areas with visual symptoms of nutrient deficiency, flooding and drainage conditions

In the simulation we assume that this will help to reduce the risk of waterlogging (in high rainfall regions this may be critical).

10. Composting

Composting organic waste and using compost and green fertilizers. Farmers can combine compost with other source of nutrients with specific amounts of compost application required.

In the simulation we assume that this can increase soil organic matter. However, proper application may be complicated and may require systems of fertigation. It may also be hard to get farmers to carry the stems back from the processing center to a compost pile (according to experts).

11. Nutrient management

To maintain soil fertility growers have regular analysis of nutrients with soil tests. Nutrient management practices are implemented based on assessment of crop needs, regular monitoring of soil fertility and crop nutrient status, or recommendations from local agronomic experts. Regular soil tests and (visual) leaf tests are done, including macronutrients and organic matter. Samples are generalizable and are analyzed as often as possible.

In the simulation we assume that this will offer a basis for good nutrient management. It may help farmers to reduce chemical fertilizer applications, increasing banana yields and providing economic and environmental benefits.

12. Integrated Pest Management (IPM)

Develop an integrated pest management (IPM) plan and follow regulations on sprays of pesticides. They keep a list of the pesticides with names of active ingredients and crops on which the pesticides are used and the targeted pests. They implement at least 2 activities per registered crop that include the adoption of production practices that could reduce the incidence and intensity of pest attacks, and thereby reduce the need for intervention. They take part in training on integrated pest management including monitoring of pests and diseases, alternative ways to control pests and diseases, preventive measures against pests and diseases, measures to avoid that pests and diseases build up resistance to pesticides. Access to and guidance from an expert in integrated pest management (IPM).

In the simulation we assume that this will help to reduce chemicals used which will decrease production costs and emissions from chemical manufacturing. IPM is considered an effective measure for avoiding economic losses due to pest incidence.

13. Reincorporate crop residues

Mulching with organic waste material.

In the simulation we assume that this means that the banana residue is retained in the field. This could also contribute to reducing organic waste from the plantation.

14. Cover crops

Ground cover / cover crops to reduce water and wind erosion, avoid bare soil and ensure soil fertility and improved soil structure.

In the simulation we assume that this could reduce weed infestation, reduce soil erosion, and nutrient losses from leaching (cover crop as catch crop).

15. Buffer zone

Planting vegetative buffers at the edges of cropped fields. Maintain existing riparian buffer zones around aquatic ecosystems, bodies of water and watershed recharge areas and between production and areas of high conservation value, either protected or not. Pesticides, hazardous chemicals and fertilizers are not applied in buffer zones.

In the simulation we assume that this will mainly have ecological benefits (e.g pesticide runoff and drift, diversity corridors). The implementation of buffer zones may be costly and also have trade-offs with the yield (area sacrificed to buffer zones). The zones can provide economic benefits if sustainable timber harvests are allowed in this areas.

16. Conversion of unproductive land

Convert unproductive sites into conservation areas where viable. Develop a map that includes natural ecosystems and agroforestry canopy cover or border plantings with estimated vegetation coverage and estimated percentage of native species composition and progressively increase or restore native vegetation: adjacent to aquatic ecosystems, farmed areas of marginal productivity, around housing and infrastructure. Use live fences, shade trees, and permanent agroforestry systems.

In the simulation we assume that that the unused land areas are likely to be a rather small proportion of the total land. There will be ecological benefits and other harvests (e.g. from the agroforestry systems).

17. Recycling plastic

Plastic wastes are separated and recycled.

In the simulation we assume that this will mainly have ecological benefits.

18. Waste plan

A waste management plan that includes strategies in waste reduction, recycling, reuse and disposal alternatives. This plan establishes timelines by when the company will identify the main wastes, ways to reduce and reuse them if applicable, and to dispose of them in the best available way.

19. Plastic reduction

Reducing plastic use i.e. instead of using the standard pre-cut impregnated plastic bags for fungicide application farmers can use a fitted bag or roll of specialized plastic.

In the simulation we assume there is an increased labor cost when using the replacement plastics. Plastic reduction may reduce the cost and provide environmental impacts.

20. Plastic re-use

Re-using plastics, such as the bags used for fungicide application.

In the simulation we assume there is an increased labor cost when collecting and re-using plastics. Plastic re-use may reduce production costs and provide environmental benefits.

Effectiveness of measures for climate in banana certification

We estimated the effectiveness of the measures based on three main aspects: adaptation and mitigation to climate change and the effects of the measure on the ecological system. To simulate adaptation effects we quantified the total benefits of the measures and compared those with the costs required to implement them. To estimate mitigation effects we quantified the effects of the measures on global greenhouse gas emissions. Finally, to estimate the ecological impacts we quantified the effects of the measure on surrounding biodiversity and habitats.

For variable inputs to the decision model we generated a table of 90% confidence estimates (**see Annex**). Each of these estimates represents the expected difference in percentage given the measure implementation. For example we estimated the costs of a certification measure as the difference in percentage relative to the total farm production costs due to the measure.

Theoretical framework

A theoretical framework for a typical banana production scheme in Latin America (Fig. 2) considers relationships of the system with components of the atmosphere, lithosphere and hydrosphere. This figure was adapted from existing literature (Hernandez and Witter 1996).

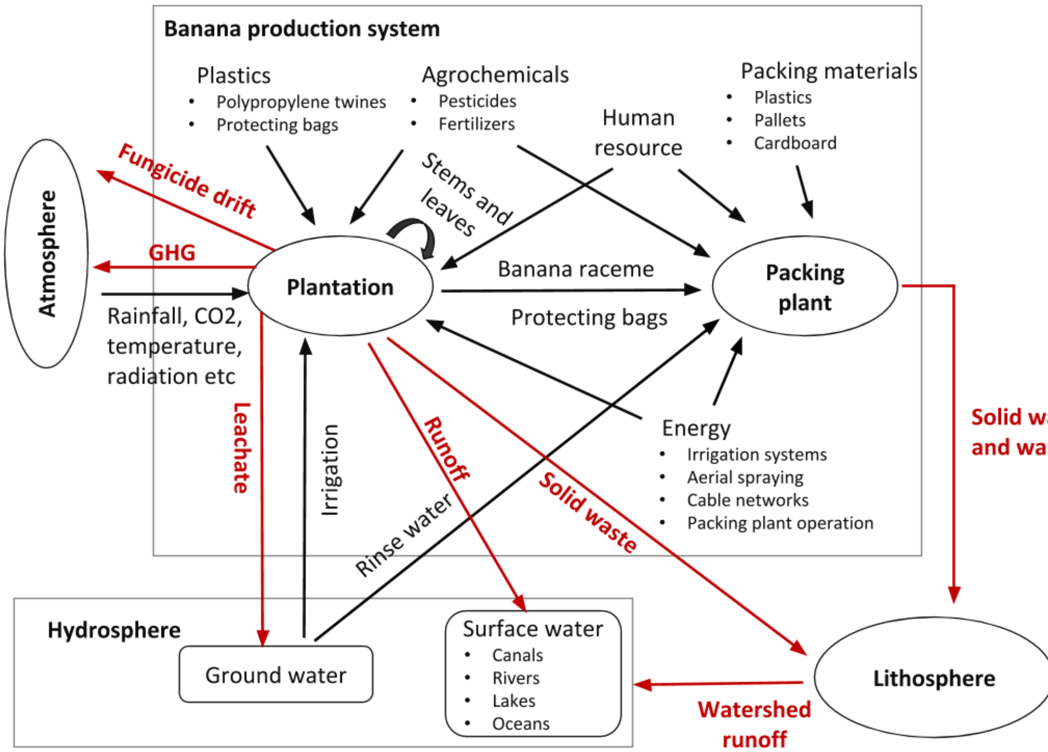


Figure 2: Framework describing a typical export-oriented banana plantation in Latin America, including internal and external components of the production system. The figure characterizes components of a typical commercial banana production system and interactions with the system's surrounding environment (i.e atmosphere, lithosphere and hydrosphere). Incoming arrows indicate the inputs going into the components, outgoing arrows represent outputs of the components. Red arrows are the main environmental problems that the proposed measures are expected to address.

In order to include and relate these relationships with the provided list of measures, we disaggregated and shortened the initial list of interventions and formulated frameworks that represent the general causal structure of the expected impact of the various certification measures.

These conceptual models were necessarily incomplete since we are working with agricultural systems and unlimited possibilities of interactions can still be drawn. To ensure that the models were as complete as possible we updated them through an extensive literature review, interviews and questionnaires with several experts (**see Annex**).

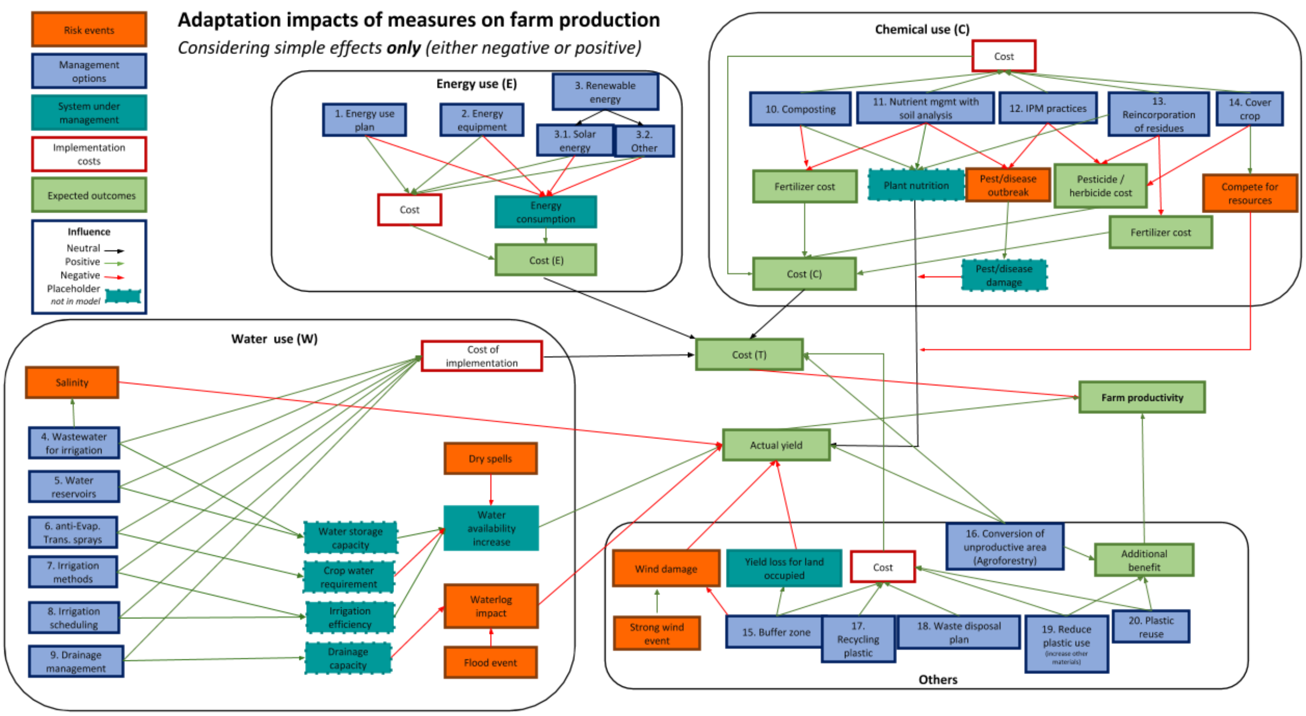


Figure 3: Conceptual model of adaptation impacts expected from certification measures (to guide model development). To estimate adaptation effects we quantified the total benefits of the measures and compared those with the costs required to implement them.

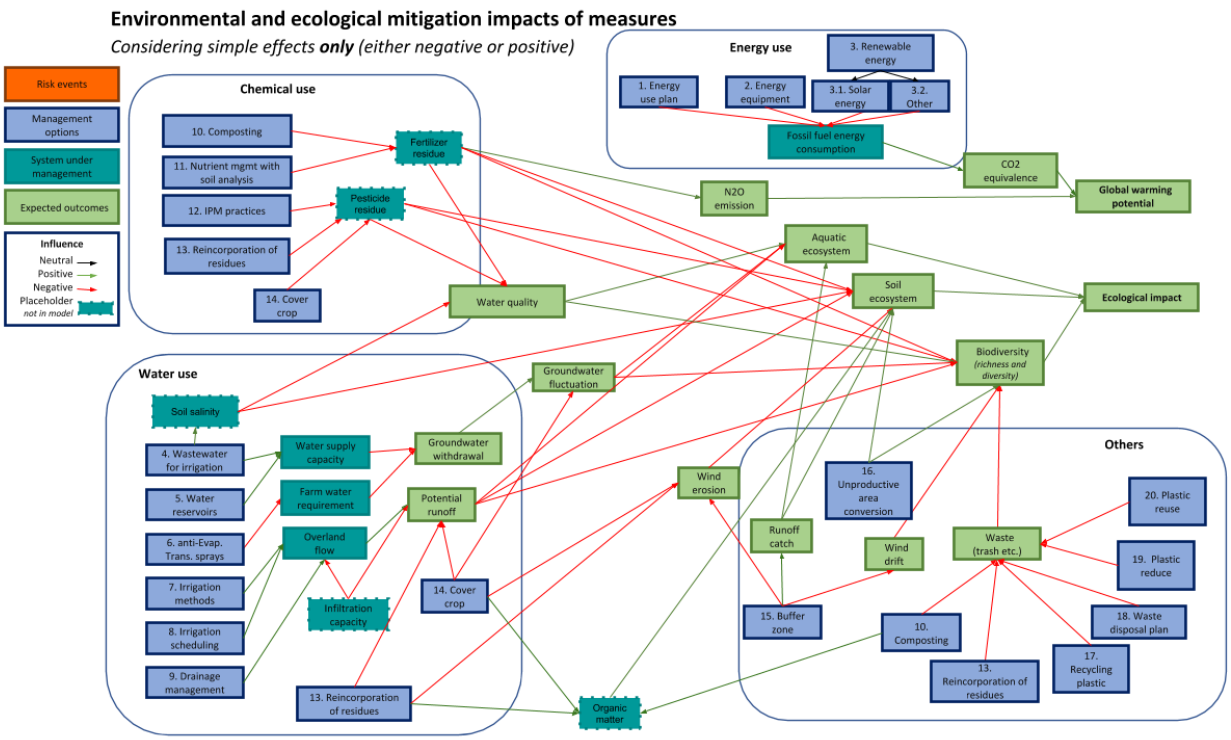


Figure 4: Conceptual model of mitigation and environmental impacts expected from certification measures (to guide model development). To estimate climate change mitigation impacts we quantified the effects of the measures on global greenhouse gas emissions. To estimate the ecological impacts we quantified the effects of the measure on surrounding biodiversity and habitats.

Model function

We used the conceptual models as frameworks to inform the process of generating a simulation of the relative impacts of certification measures (expected change from banana production without the measures). First, we developed a general function that estimates costs, benefits, risk reduction, risk increase (for which we did not find much evidence, so that this was omitted from the final summary figures), adaptation and mitigation to climate change, and the ecological impact of any certification measure. This allowed us to obtain a common output structure independent of the certification measure evaluated (**see Annex**). The simulation was run to represent 10 years of a typical banana production system.

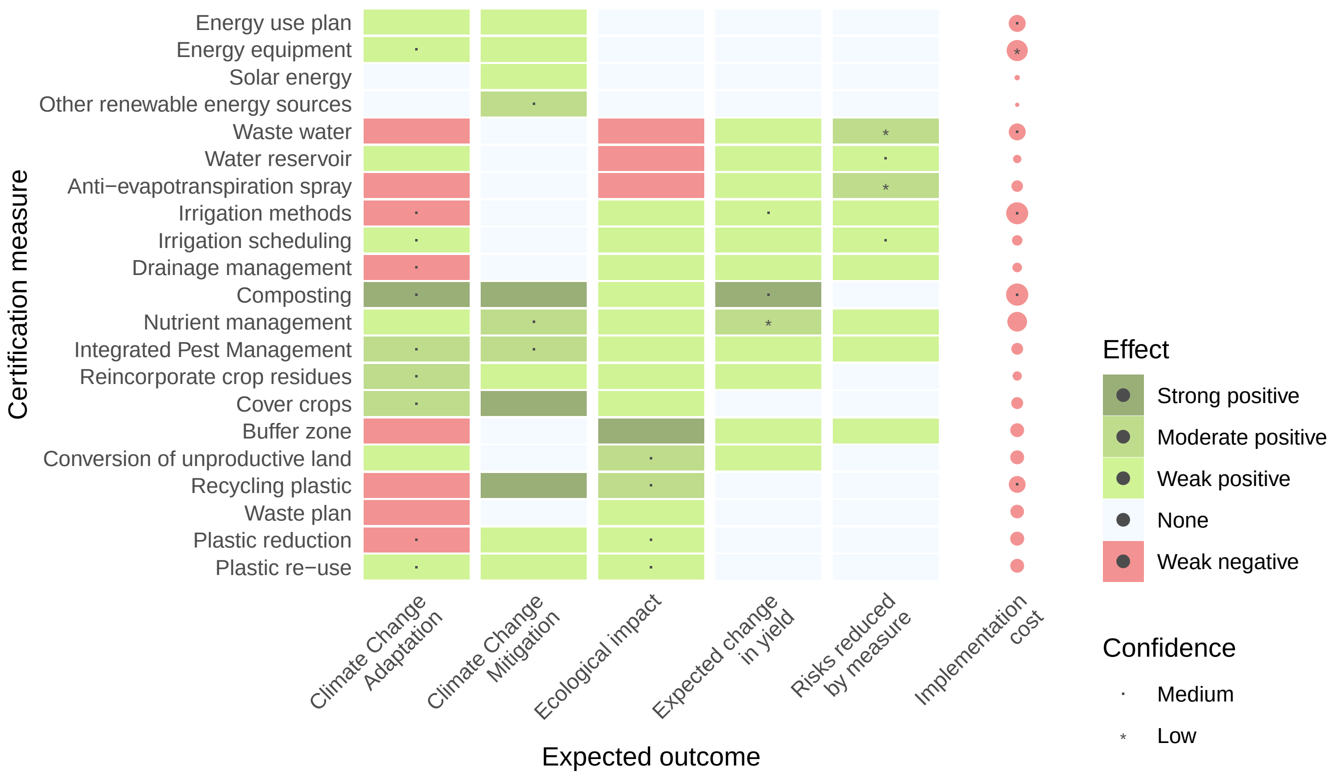
Later, we applied this function to all certification measures using the specific information we gathered for each.The ultimate aim was to get a list of the measures that influence adaptation, mitigation and environmental outcomes (see `return()` list at the end of the `certification_measures_function`) (**see Annex**).

After coding the impact pathways we performed a Monte Carlo simulation with the `mcSimulation()` function from `decisionSupport`. This function generates a distribution representing the desired outputs (see `return()` function above) by calculating random draws in our defined `certification_measures_function()`. Inside this simulation we use a generalized function called `certification_impact()` to establish the possible impacts of each measure.

```
source("certification_measures_function.R")
certification_measures_simulation <- mcSimulation(
  estimate = estimate_read_csv("certification_measures_input_table.csv"),
  model_function = certification_measures_function,
  numberOfModelRuns = 1e2, #100 for now
  functionSyntax = "plainNames"
)
```

Results

According to our simulation the certification measures that were most effective in terms of adaptation to climate change impacts were cover crops, composting, reincorporation of crop residues and integrated pest management (IPM). Those measures that were most effective for climate change mitigation were composting, cover crops and recycling plastic. We also simulated the ecological impacts of the measures and found that buffer zones, conversion of unproductive land and recycling plastics had the greatest positive effect. Here we represent the model outputs with several visualizations generated with `ggplot2` showing qualitative differences between farms with and without certification measures.



Effect	Climate Change Adaptation	Climate Change Mitigation	Ecological impact	Expected change in yield	Risks reduced by measure
Strong positive	> 55%	> 50%	> 50%	> 20%	> 15%
Moderate positive	30 to 55%	25 to 50%	25 to 50%	10 to 20%	8 to 15%
Weak positive	0 to 30%	0 to 25%	0 to 25%	0 to 10%	0 to 8%
None	0%	0%	0%	0%	0%
Weak negative	< 0%	< 0%	< 0%	< 0%	< 0%

Figure 5: Qualitative differences between farms with and without certification measures. We classified the expected effect according to the thresholds shown in the table. These thresholds represent the median of 10,000 simulations of the expected change with the certification measure. We describe the confidence in our assignment of outcomes to these classes according to the percentage of the total simulations that fell in the same class.

This heatmap shows the expected impact of the proposed certification measures in greater detail. Here the bubbles represent the interquartile ranges, colors show the ranges of positive and negative effects.

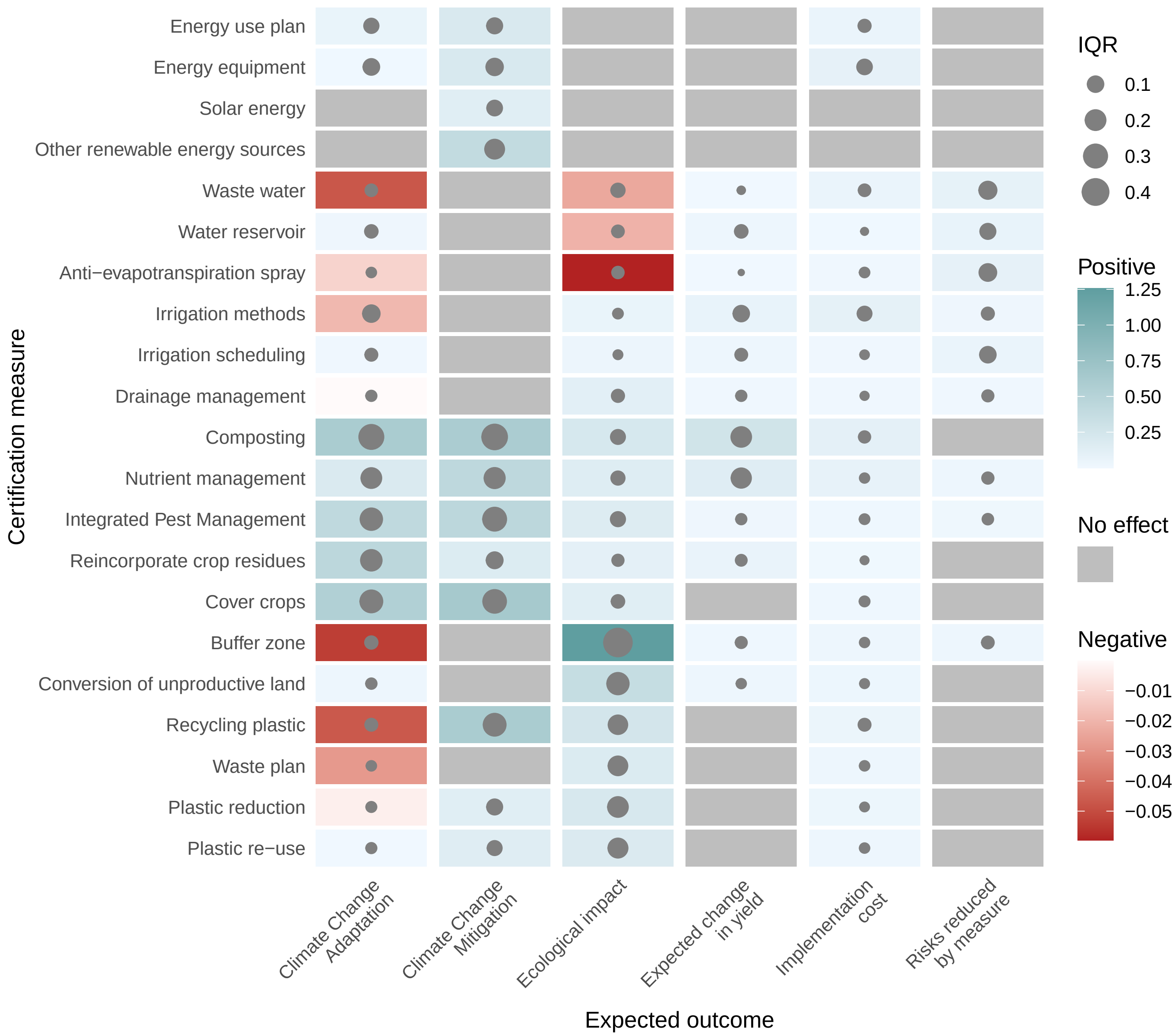


Figure 6: Qualitative differences between farms with and without certification measures with interquantile ranges (IQR)

This heatmap also illustrates the mean difference between measures and no measures and provides more specific values regarding the expected effect. Colors and numbers show the median value derived from the 10,000 model runs of the Monte Carlo simulation.

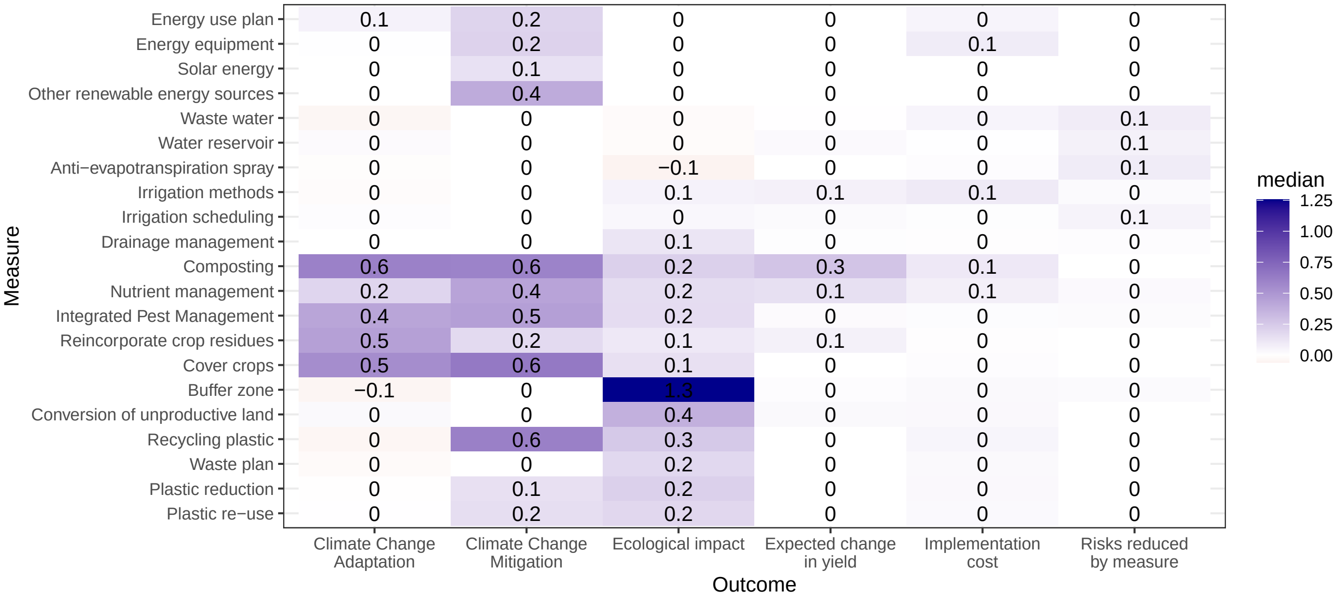


Figure 7: Relative differences between farms with and without certification measures

Prioritized list

Here we illustrate the prioritized lists of the expected effects of the certification measures on mitigation, adaptation and surrounding ecological systems. We use boxplots for this, which are useful for illustrating the spread of the data resulting from the many runs of the decision model. They show the median (central line), the 25th and 75th percentiles (sides of boxes) and any outliers (light circles outside of boxes). These boxplots represent the full distributions of 10,000 model runs of the simulations showing the expected relative farm-level difference in outcomes between implementing the certification measures and not implementing them. We use an adapted version of the `decisionSupport` `plot_distributions()` function to show an overlay of the full results for the decision options, i.e. the expected farm-level adaptation to climate change if we choose to implement the certification measure.

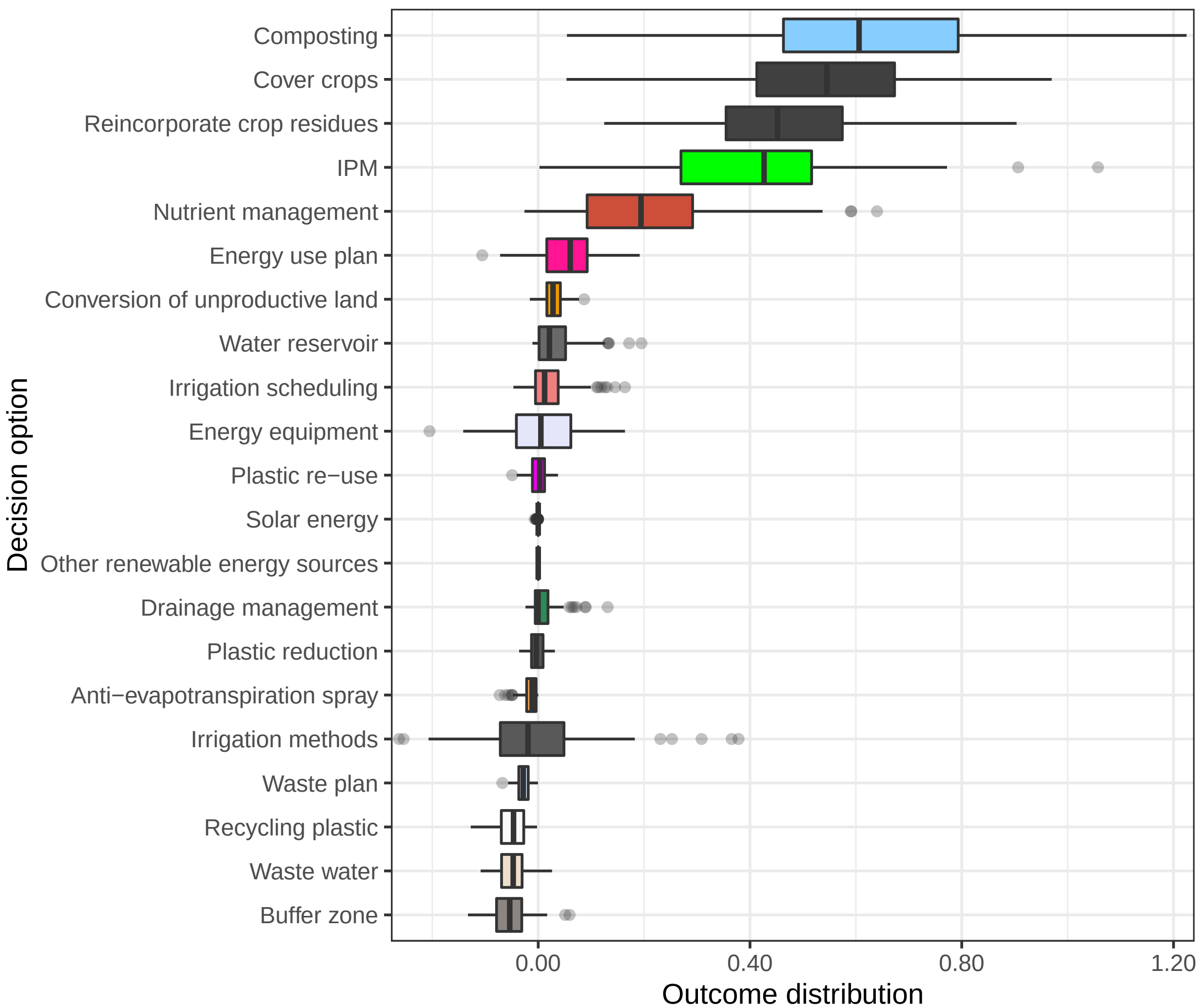


Figure 8: Certification measures ordered by relative median farm-level adaptation to climate change

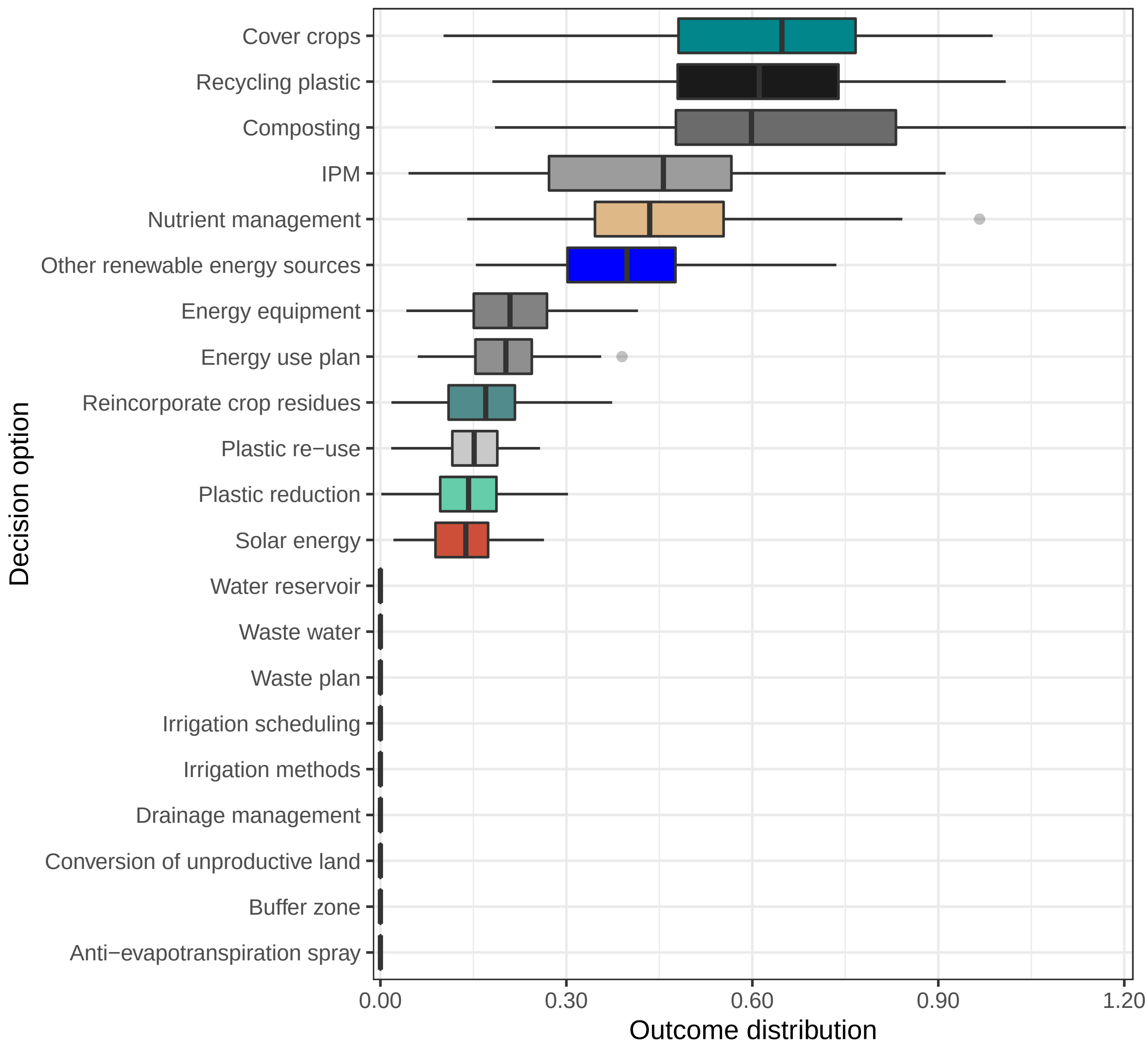


Figure 9: Certification measures ordered by relative median farm-level mitigation to climate change

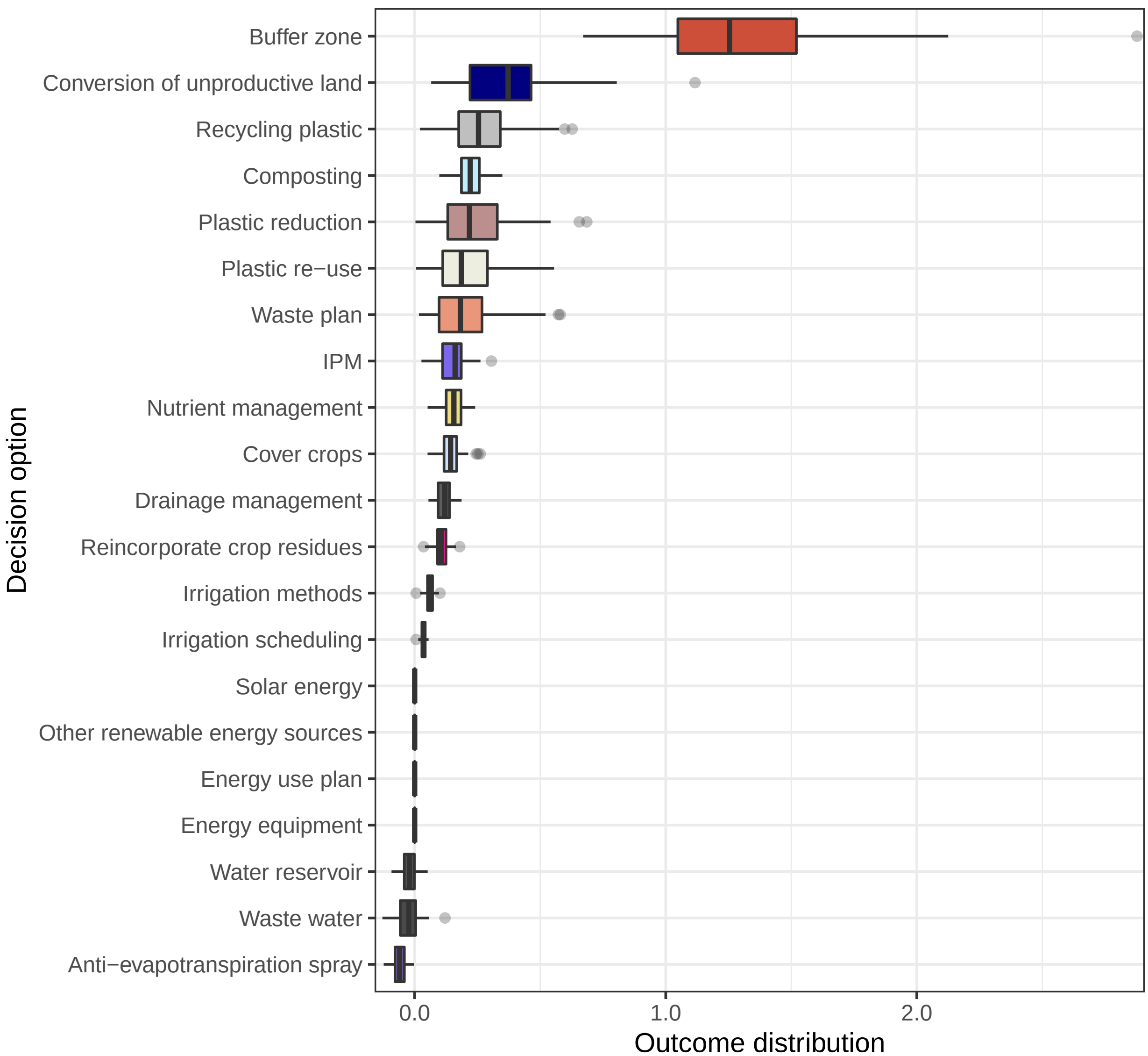


Figure 10: Certification measures ordered by relative median farm-level ecological impacts

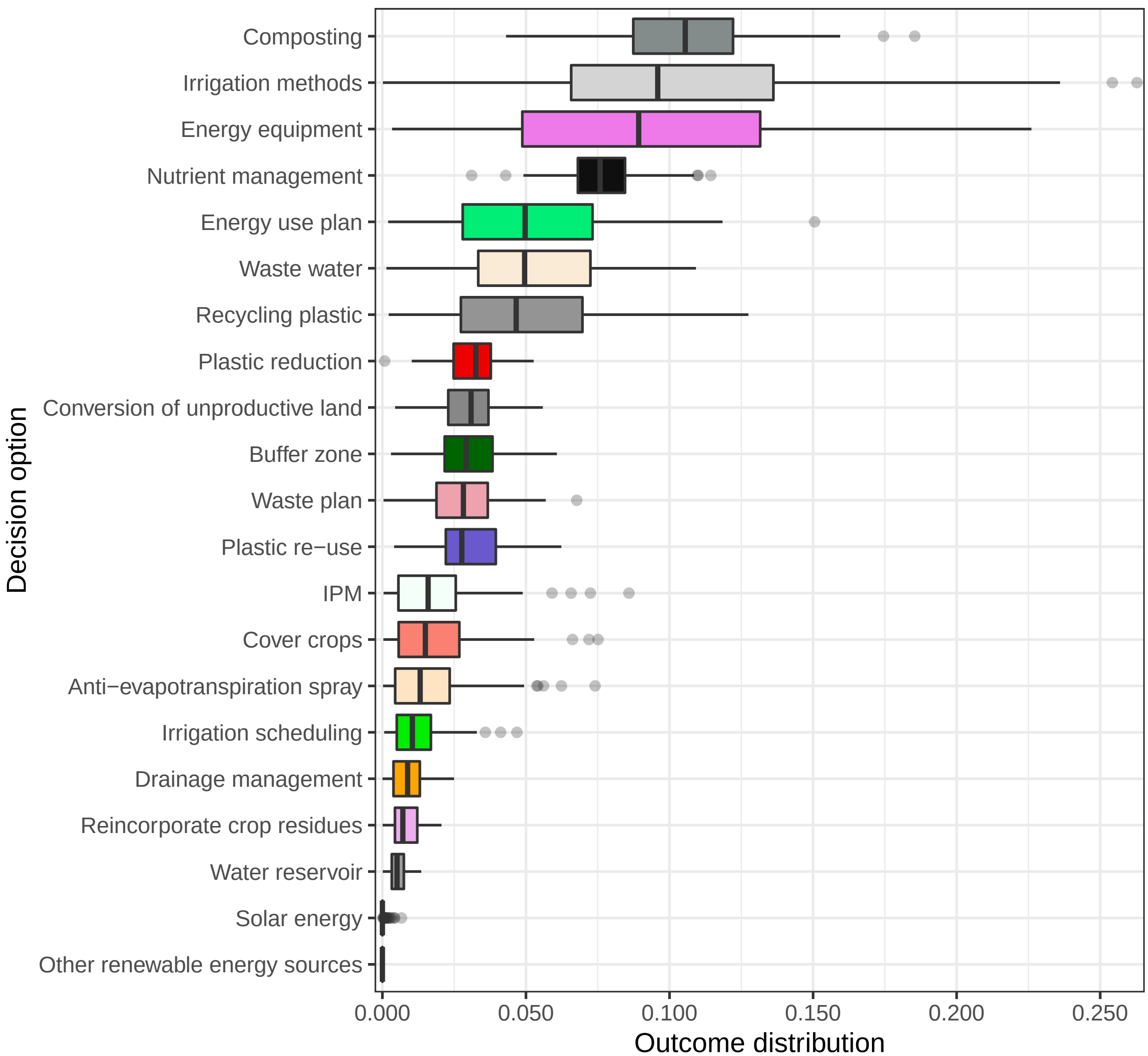


Figure 11: Certification measures ordered by relative median farm-level impacts on total costs

Recommendations

Based on the prioritized list of measures presented we recommend that the Action Alliance for Sustainable Bananas (ABNB) promote banana management measures such as cover crops, composting, reincorporation of crop residues, integrated pest management (IPM), buffer zones, conversion of unproductive land and recycling plastics. These measures appear to be among the most effective for climate change adaptation and mitigation in high rainfall export oriented banana production regions of Latin America. Similarly these measures seem to be positively related to the effects on local ecological systems.

Banana production systems are complex and dynamic, and each of the certification measures could have a number of positive or negative impacts. Our simulation does not capture the whole complexity of these interactions. Further research will be needed in order to provide more confident and comprehensive recommendations. The results presented here are specific to high rainfall export oriented banana production regions of Latin America. There is scope for applying these modeling procedures to other agroecological regions such as dry production areas of Latin America, which are often smaller farms with greater need for water use management.

Research gaps

Given the time constraints, we could not involve many local banana producers (i.e. farmers and companies). However, we feel confident that we have captured the key aspects in our model through expert interviews and an extensive literature review.

Given the diversity of banana production systems in Latin America the effectiveness of certification measures for climate change outcomes will be influenced by many factors such as soil conditions, topography, microclimates, as well as production scales and farm operations. This results in high uncertainty in the model outcomes. Any resulting recommendations should be made with consideration of the many location specific factors that might influence the effect of the certification measure.

Future research

In addition to the defined measures, climate informed advisories and weather indexed insurance are among the many other potential interventions that could help banana producers to cope with climate related risks. However, the low provisions of these services imply the need of future research on their feasibility

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Appendix

Experts consulted

We contacted 48 experts either with a link to our questionnaire in an email or via zoom or phone calls. Of these, 19 responded and those that agreed to be cited in this report are listed in the table below.

Table 1: List of banana experts consulted

Name	Role
Allan Brown	International Institute of Tropical Agriculture
Alistair Smith	Banana Link
Paul Lievens	Banana Link
Charles Staver	Bioversity International
Dave Reay	The University of Edinburgh
Fabián Calvo Romero	Rainforest Alliance
Hildegard Garming	Thünen Institute
Hugo Hays	Fyffes Global Director Food Safety and Compliance
José Joaquín Campos Arce	Sustainable Agriculture Network (SAN)
José Madriz	Agricultural expert (banana production)
Manfred Pülm	Landgard
Martin Schüller	FairTrade
Mike Port	Beclimate
Ruerd Ruben	Wageningen University & Research
Sebastien Carpentier	Alliance of Bioversity International
Thanos Papageorgoiu	Interweichert
Thomas Landwehr	Dole Hamburg
Tobias Bandel	Soil&More

Expert responses

Based on the list of measures and the prospective influence on adaption and mitigation in banana production we organized a questionnaire with seven question sections. We offered a chance for experts to decide which sections of our questionnaire they would like to respond to (with the option to answer multiple sections). The aim was to gather expert knowledge and hands-on experiences regarding the current situation of export-oriented banana production systems. This served as important source of information to justify and update the impact pathways that were the basis for our models.

There was a lot of variation in the expert responses. This reflects the high diversity of banana production settings across the various relevant agroecological zones. Therefore, any recommendations should be made with caution and may require site-specific recommendations.

1. **Buffer system, reforestation and system diversification**

We asked experts to answer several questions relating to the establishment of buffer areas, windbreaks surrounding banana plantation, the implementation of crop diversification, the management of unproductive banana cultivated areas. Buffer zones provide a wide range of ecological and environmental benefits such as protecting surface water bodies, high value biodiversity areas, human settlements from pesticide runoff and drift from the production areas and can prevent soil erosion. In some plantations, buffer zones have been established following the national legislation (e.g. in Costa Rica). In other countries, despite national mandate to have buffer areas, especially along waterways, it is not always implemented by banana producers. Experts suggested that the establishment of buffer areas in banana production systems will generate a positive ecological benefit.

When establishing buffer areas, several factors need to be taken into consideration, including topography, soil type, local vegetation and surrounding water course and human settlements. Natural vegetation with native species is recommended and should include grasses, shrubs, timber trees or a mix of the three. Grass acts as ground cover to prevent soil erosion and pesticide / sediment runoff from the banana field to the surrounding water bodies and other ecosystems while trees and shrubs break strong winds and reduce negative impacts on banana yield. They can also provide ecological habitats for diverse species. Although there should not be any cultivation in buffer areas, sustainable timber harvest could be allowed, which would provide an additional benefit.

Expert opinions vary on how wide the buffer zones should be. The minimum width appeared between 5 – 20 meters depending on slope, soil types, vegetation types and the width of watercourses. One important factor that determines the structure of these buffer zones is the ecosystems service that they are expected to provide (e.g. flood protection, stream bank stabilization, erosion reduction, prevent pesticide runoff and drift).

Crop diversification seems to be unlikely to be adopted in large-scale commercial banana production systems. Intercropping and rotation increase production cost (mostly labor cost for harvesting) and make uniform aerial spraying for controlling fungal infection difficult. Rotations and annual replanting are restricted by existing infrastructure. However, in the context of climate change, crop diversification will be crucial to reduce risk of production and enhance ecological and climate change resilience. Crop diversification could be practical with landscape consideration. In commercial small-scale agroforestry systems or agroecological production with diversified crops such as other banana varieties than Cavendish alone, pineapple, cashew etc., could be feasible. Diversification can also be achieved to some extent through ground cover and diversity corridors (i.e. buffer zones) or the conversion of unproductive banana cultivation areas (e.g. implement agroforestry or promote natural vegetation). The support of consumers also plays a part in the promotion of crop diversification (e.g. certain specialized markets may pay for agroforestry banana). This is however still rare in bulk consumption markets.

2. **Irrigation and drainage**

We asked experts to answer several questions about the water use in the banana production. The questions focus on irrigation and drainage techniques that have been used and their effectiveness to cope with climatic risks Supply source of water to banana production varies greatly with locations. Most experts acknowledge rainfall, ground water and surface water bodies (e.g. rivers, lakes, ponds, streams) as the main water supply. In Andean banana producing countries, water from the mountains (i.e. glaciers/snow field) is also considered an important supply in addition to the rainwater. However, this mountain water is expected to reduce and may even disappear in the near future. The production might become unsustainable. The experts agreed that many banana production systems may be facing water shortages at some point.

Waste water from packing plants has been proposed to be used for irrigation. However, risks of salinity, contamination of heavy metal and other phytotoxic material, as well as health risks to workers have been raised by experts. In addition, wastewater from banana processing contains latexes that might impact soils and the banana fields. Experts agreed that the waste water should undergo a proper treatment before being used. The contribution of waste water to irrigation could be insignificant. Under canopy single and series sprinkler irrigation appeared to be the most common irrigation technique in banana production. Experts agree that this is a high efficiency method. In addition, furrow irrigation, flood irrigation and drip irrigation are the other applied techniques. The former two are considered low efficiency. Drip irrigation would perform well in semi-arid areas where availability of water is low.

Anti-transpirants is not considered an effective option in humid areas to compensate climate change induced high evapotranspiration. The performance of this method depends on aspects of production like the microclimate and temperature and the soil water status.

Open systems with water channels along the banana plots is common drainage system, which performs sufficiently to avoid waterlog. For a highly efficient drainage system design, meteorological data should be employed for rough calculation. It is also important to consider field soil parameters (i.e. infiltration rate). Drainage systems can work as a part of an adaptive management approach. Therefore, field monitoring, observation, evaluation and calculation could be done to design an optimal system. This approach has been implemented by farms who have demonstrated good farm performance. It is also suggested that drainage channels should be larger than the existing ones.

3. **Pest management**

We asked experts to answer several questions about pest control practices applied by banana producers and potential sustainable ways for pest management. Integrated Pest Management (IPM) practices have been promoted and recommended in all agricultural production settings thanks to its comprehensive combination of diversity control approaches. The application of IPM varies across the regions and the markets. These approaches are more likely to be applied in large plantations than in small-scale producer cooperatives. Farms who follow the voluntary sustainability standards (VSS) (e.g. Fairtrade or Rainforest Alliances) are already required to implement IPM practices.

Spraying decisions are mostly made based on the spraying regulation from VSS or other certification scheme, also on farm monitoring to ensure compliance and to reduce the risk of crop loss. Some are based on farmer experiences which are normally not data driven. Historical production data are not used effectively in the spraying decisions. Herbicide application remains a common method to control weeds in most banana plantations. Herbicide has been used in combination with other methods such as ground cover or manual weeding with hand operated equipment. Ground cover is considered an effective control for weeds and can reduce the use of herbicide. Ground cover could be made up of naturally occurring plants, selected over time for their low competition with bananas, banana plant residues or a combination of banana plant residues and cover crops. Some farmers feel strongly that the cover crops compete with bananas and others fear that the cover crops can harbor dangers for workers (snakes etc.).

The application of mechanical and biological controls in pest management are considered a good method compared to chemical measures when considering factors of human and environmental health. However, in economic terms, these measures are equally or less effective but are more labor intensive. Mechanical measures might also increase the risks of disease infection from contaminated tools. Chemical measures also could induce secondary pest outbreak.

In large-scale banana production, automated technical tools are sometimes used for disease monitoring. Some farms are so advanced as to use drones equipped with GPS for guiding aerial spraying.

4. **Soil and plant nutrient**

We asked experts to answer several questions about soil and plant nutrients and how banana growers manage soils during production Common fertilizer application methods include side dressing (most common), through irrigation and foliar application.

Banana plantations are characterized by long periods of production (3-5 years, 20-25 years in some places). Due to the fact that the roots of banana plants are very superficial, no or very little tillage is done until the banana plots need to be replanted. Therefore, reduced tillage is not likely a necessary cultivation practice here.

Compost does play a part in the nutrient supply; however, it is not very commonly practiced. Composting materials are derived mainly from on-farm biomass, a small portion can come from external plant biomass. Composting is also considered an effective management for farm organic waste. Big farms sometimes have composting plants however it is prohibitively expensive for small scale farms. Application of compost is also labor intensive and that can make it unlikely to be adopted.

Plant residues could also be reincorporated to the field to serve as soil cover. This would have a low cost and is expected to have several benefits (i.e. organic matter, positive impacts on nematode control).

5. **Waste management**

We asked experts to answer several questions about organic and inorganic waste generated in banana production systems. The management of organic waste has been mentioned in the previous section (i.e. it is for compost or reincorporated into the field as soil cover). Therefore, inorganic waste is the focus of this section.

Plastic wastes are considered to be a problem in banana plantations of any production scale. Pesticide impregnated plastics bags and pesticide containers pose risks including contaminated ground water and other surface water bodies. Appropriate treatment of these materials is needed. Reducing use, re-using bags and recycling and/or proper disposal of all the plastic waste are suggested as options to manage these sources of waste.

6. **Energy system**

We asked experts to answer several questions about implementation of measures related to energy. There were several options identified. These were considered to have a positive effect on mitigation in the extent to which they reduced the use of fossil fuels. Investments into more energy-efficient equipment could save energy. However, the measure was not considered to be one that would have a major impact on fuel consumption.

Some banana plantations (i.e. in Costa Rica) already have electricity from renewable sources. External renewable energy supplies are rare in most banana plantation areas. Solar, wind and biomass energy could be potential sources. Solar panels are considered to have high installation and maintenance costs, this is likely also the case with wind power. Biomass energy could be used in the form of biogas in small scale plantations. In large scale, biomass energy is constrained by input availability, high cost and resource trade-offs. Some other renewable sources such as hydropower, geothermal energy are mentioned but only feasible in mountainous regions with high rainfall or under specific conditions such as volcanic islands. Using a single source of renewable energy could result in energy supply shortages and use of various sources would prevent this.

7. **Risks**

We asked experts to answer several questions about different risks to banana plantations. We also asked about measures that have, or could have, potential to reduce the negative impacts of risks.

In the climates where banana is cultivated, storms with strong wind, extreme rain events, flooding and drought appeared as the greatest risks. They can cause massive production damage and loss of yield. Hail can also be an issue.

Pest and disease outbreaks are also a major risk and can be amplified by severe weather. The impacts of those risks are not generalizable to all production locations, therefore farm-level coping measures can be diverse. Good drainage systems, windbreaks, drip irrigation, water harvesting, crop diversification, targeted fertilizer application, reforestation of upstream catchment areas, robust disease control systems, early warning systems, use of high-quality seedlings were all listed as possible control mechanisms.

Model simulation code

General function to estimate costs, benefits, risk reduction, risk increase, adaptation and mitigation to climate change, and the ecological impact of any certification measure.

```
# function to calculate the 5 outputs of certification measures

certification_impact <- function(cost_measure,
                                 # general yield benefit (without risk)
                                 yield_benefit,
                                 additional_benefits,
                                 event_risk,
                                 normal_damage,
                                 reduction_damage_measure,
                                 # second risk (risk caused by measure)
                                 negative_risk_event_measure,
                                 normal_damage_not_from_measure,
                                 increase_damage_by_measure,
                                 mitigation_factors,
                                 soil_quality,
                                 water_quality,
                                 biodiv_richness,
                                 var_CV, n_years) {

  # Positive effect of measure on a risk ####

  # create a vector of years with any risk events
  # these are independent of the measure, they just happen, like major weather events
  # (hurricane)
  event_years <-  chance_event(event_risk, n = n_years)

  # calculate yield before intervention
  # i.e. what is the yield before the measure decreases that risk
  yield_no_measure <- ifelse(event_years,
                             yes = 1 - normal_damage,
                             no = 1)

  yield_measure <- ifelse(event_years,
                          yes = 1 - (normal_damage * (1 - reduction_damage_measure)),
                          no = 1)

  # relative mean annual yield with independent risk
  yield_positive_impact <- mean(yield_measure - yield_no_measure)
```

```r
  # Negative effect of measure on risk ####

  #create a vector of years with risk events that the measure has a positive influence on
  #i.e. the measure will increase the risk (like waste water increases risk of salinity)
  negative_risk_event_measure_years <-  chance_event(negative_risk_event_measure,
                                                     n = n_years)

  # calculate yield before measure
  # i.e. what is the yield before the measure increases that risk
  yield_no_negative_risk_event_measure <- ifelse(negative_risk_event_measure_years,
                                                 yes = 1 - normal_damage_not_from_measure,
                                                 no = 1)

  yield_negative_risk_event_measure <- ifelse(negative_risk_event_measure_years,
                                              yes = 1 - (normal_damage_not_from_measure *
                                                         (1 + increase_damage_by_measure)),
                                              no = 1)

  # relative mean annual yield with a risk that is increased by the measure
  # (i.e. waste water and salinity)
  yield_negative_impact <- mean(yield_negative_risk_event_measure -
                                yield_no_negative_risk_event_measure)

  #estimate one unique yield given interactions of the measure
  # use the yield_negative_impact and yield_positive_impact from above
  # use the '+' because yield_negative_impact should always be negative
  yield <- yield_positive_impact + yield_negative_impact +
    # in the case that there is no risk event this is the yield benefit
    mean(vv(yield_benefit, var_CV, n_years))

  # use chance_event to calculate the relative mean risk reduction with measure
  risk_reduction <- mean(
    chance_event(
      event_risk,
      # normal damage vs. the percentage damage reduced by measure
      value_if = (normal_damage * (1 - reduction_damage_measure)),
      value_if_not = 0,
      CV_if = var_CV,
      CV_if_not = 0,
      n = n_years
    )
  )

 # use chance_event to calculate the relative mean risk increase from measure
  # the measure increases the risk
  risk_increase <- mean(
    chance_event(
      negative_risk_event_measure,
      # normal damage vs. the percentage damage reduced by measure
      value_if = (normal_damage_not_from_measure * (1 + increase_damage_by_measure)),
      value_if_not = 0,
      CV_if = var_CV,
      CV_if_not = 0,
    )
  )
```

```
  # relative mean benefits of measure
  # calculate yield to any additional benefits
  # can also be manipulated to be 'negative benefits' in case of disadvantages
  benefits <- yield + mean(vv(additional_benefits, var_CV, n_years))

  # total costs over n_years
  cost <- mean(vv(cost_measure, var_CV, n_years))

  if(cost < 0) cost <- 0

  # relative mean adaptation impacts
  adaptation <- benefits - cost

  # mitigation here is the mean of any reductions in parameters related to global
  # warming potential
  mitigation <- mean(vv(mitigation_factors, var_CV, n_years))

  # simple ecological impact based on soil, water, biodiversity effects

  # how will ecological parameters change if measure is applied
  soil_impact <- mean(vv(soil_quality, var_CV, n_years))

  water_impact <- mean(vv(water_quality, var_CV, n_years))

  biodiv_richness_impact <- mean(vv(biodiv_richness, var_CV, n_years))

  # sum all and divide by 100 because inputs are norm not t_norm_0_1
  ecology <- sum(soil_impact, water_impact, biodiv_richness_impact)/100

  # define the outputs of the general function
  return(list(yield = yield,
              cost = cost,
              risk_increase = risk_increase,
              risk_reduction = risk_reduction,
              adaptation = adaptation,
              mitigation = mitigation,
              ecology = ecology
              ))
}
```

Simulation of certification measures that influence adaptation, mitigation and environmental outcomes (see `return()` list at the end of the `certification_measures_function`).

```
# Source the general certification impact function

source("certification_impact.R")

# The model function estimating the outputs for every certification measure
# (i.e. impact of measures on farm productivity, cost associated to the measure,
# etc.) ####

certification_measures_function  <- function(){

  # use the sum of the 10 years of simulation to compare across interventions
  # the function is defined in the certification_impact.R file

  ### Relative impact of the energy measures:
```

```r
# Intervention 1: Energy use plan ####
certification_impact_energy_use_plan <-
  certification_impact(cost_measure = cost_energy_use_plan,
                       yield_benefit = 0,
                       additional_benefits = energy_saved_use_plan,
                       event_risk = 0,
                       normal_damage = 0,
                       reduction_damage_measure = 0,
                       # second risk (risk caused by measure)
                       negative_risk_event_measure = 0,
                       normal_damage_not_from_measure = 0,
                       increase_damage_by_measure = 0,
                       mitigation_factors = increase_efficiency_energy_use_plan +
                         reduced_fossil_fuel_consumption_energy_use_plan,
                       # ecological impacts
                       soil_quality = 0,
                       water_quality = 0,
                       biodiv_richness = 0,
                       var_CV = var_CV, n_years = n_years)

energy_use_plan_yield <- certification_impact_energy_use_plan$yield
energy_use_plan_cost <- certification_impact_energy_use_plan$cost
energy_use_plan_risk_increase <- certification_impact_energy_use_plan$risk_increase
energy_use_plan_risk_reduction <- certification_impact_energy_use_plan$risk_reduction
energy_use_plan_adaptation <- certification_impact_energy_use_plan$adaptation
energy_use_plan_mitigation <- certification_impact_energy_use_plan$mitigation
energy_use_plan_ecology <- certification_impact_energy_use_plan$ecology

# Intervention 2: Energy equipment  ####
certification_impact_energy_equipment <-
  certification_impact(cost_measure = cost_energy_equipment,
                       yield_benefit = 0,
                       additional_benefits = energy_saved_energy_equipment,
                       event_risk = 0,
                       normal_damage = 0,
                       reduction_damage_measure = 0,
                       # second risk (risk caused by measure)
                       negative_risk_event_measure = 0,
                       normal_damage_not_from_measure = 0,
                       increase_damage_by_measure = 0,
                       mitigation_factors = increase_efficiency_energy_equipment +
                         reduced_fossil_fuel_consumption_energy_equipment,
                       # ecological impacts
                       soil_quality = 0,
                       water_quality = 0,
                       biodiv_richness = 0,
                       var_CV = var_CV, n_years = n_years)


energy_equipment_yield <- certification_impact_energy_equipment$yield
energy_equipment_cost <- certification_impact_energy_equipment$cost
energy_equipment_risk_increase <- certification_impact_energy_equipment$risk_increase
energy_equipment_risk_reduction <- certification_impact_energy_equipment$risk_reduction
energy_equipment_adaptation <- certification_impact_energy_equipment$adaptation
energy_equipment_mitigation <- certification_impact_energy_equipment$mitigation
```

```
energy_equipment_ecology <- certification_impact_energy_equipment$ecology

# Intervention 3.1: Solar energy ####
# some potential savings of going off the grid
certification_impact_solar_energy <-
  certification_impact(cost_measure = cost_solar_energy, #diff from baseline
                       yield_benefit = 0,
                       additional_benefits = energy_saved_solar_energy,
                       event_risk = 0,
                       normal_damage = 0,
                       reduction_damage_measure = 0,
                       # second risk (risk caused by measure)
                       negative_risk_event_measure = 0,
                       normal_damage_not_from_measure = 0,
                       increase_damage_by_measure = 0,
                       mitigation_factors = increase_efficiency_solar_energy +
                         reduced_fossil_fuel_consumption_solar_energy,
                       # ecological impacts
                       soil_quality = 0,
                       water_quality = 0,
                       biodiv_richness = 0,
                       var_CV = var_CV, n_years = n_years)


solar_energy_yield <- certification_impact_solar_energy$yield
solar_energy_cost <- certification_impact_solar_energy$cost
solar_energy_risk_increase <- certification_impact_solar_energy$risk_increase
solar_energy_risk_reduction <- certification_impact_solar_energy$risk_reduction
solar_energy_adaptation <- certification_impact_solar_energy$adaptation
solar_energy_mitigation <- certification_impact_solar_energy$mitigation
solar_energy_ecology <- certification_impact_solar_energy$ecology

# Intervention 3.2: Other renewable energy sources ####
# some potential savings of going off the grid
certification_impact_other_energy <-
  certification_impact(cost_measure = cost_other_energy, #diff from baseline
                       yield_benefit = 0,
                       additional_benefits = energy_saved_other_energy,
                       event_risk = 0,
                       normal_damage = 0,
                       reduction_damage_measure = 0,
                       # second risk (risk caused by measure)
                       negative_risk_event_measure = 0,
                       normal_damage_not_from_measure = 0,
                       increase_damage_by_measure = 0,
                       mitigation_factors = increase_efficiency_other_energy +
                         reduced_fossil_fuel_consumption_other_energy,
                       # ecological impacts
                       soil_quality = 0,
                       water_quality = 0,
                       biodiv_richness = 0,
                       var_CV = var_CV, n_years = n_years)


other_energy_yield <- certification_impact_other_energy$yield
other_energy_cost <- certification_impact_other_energy$cost
```

```
other_energy_risk_increase <- certification_impact_other_energy$risk_increase
other_energy_risk_reduction <- certification_impact_other_energy$risk_reduction
other_energy_adaptation <- certification_impact_other_energy$adaptation
other_energy_mitigation <- certification_impact_other_energy$mitigation
other_energy_ecology <- certification_impact_other_energy$ecology

### Relative impact of the water use measures:

# Intervention 4: Using waste water for irrigation ####
certification_impact_waste_water <-
  certification_impact(cost_measure = cost_waste_water_use,
                       yield_benefit = 0,
                       additional_benefits = 0,
                       event_risk = dry_spells_risk,
                       normal_damage = normal_dry_spell_damage,
                       # packing is done daily during harvests and this uses a
                       # lot of water
                       reduction_damage_measure = waste_water_deficit_reduction,
                       # second risk (risk caused by measure)
                       negative_risk_event_measure = salinity_risk,
                       normal_damage_not_from_measure = normal_salinity_damage,
                       increase_damage_by_measure = waste_water_salinity_damage,
                       mitigation_factors = 0,
                       # ecological impacts
                       soil_quality = soil_quality_waste_water,
                       water_quality = water_quality_waste_water,
                       biodiv_richness = biodiv_richness_waste_water,
                       var_CV = var_CV, n_years = n_years)


waste_water_yield <- certification_impact_waste_water$yield
waste_water_cost <- certification_impact_waste_water$cost
waste_water_risk_increase <- certification_impact_waste_water$risk_increase
waste_water_risk_reduction <- certification_impact_waste_water$risk_reduction
waste_water_adaptation <- certification_impact_waste_water$adaptation
waste_water_mitigation <- certification_impact_waste_water$mitigation
waste_water_ecology <- certification_impact_waste_water$ecology


# Intervention 5: Using water reservoirs for irrigation ####
certification_impact_water_reservoir <-
  certification_impact(cost_measure = cost_water_reservoir,
                       yield_benefit = 0,
                       additional_benefits = 0,
                       event_risk = dry_spells_risk,
                       normal_damage = normal_dry_spell_damage,
                       reduction_damage_measure = reservoir_water_deficit_reduction,
                       # second risk (risk caused by measure)
                       negative_risk_event_measure = 0,
                       normal_damage_not_from_measure = 0,
                       increase_damage_by_measure = 0,
                       mitigation_factors = 0,
                       # ecological impacts
                       soil_quality = 0,
                       water_quality = water_quality_water_reservoir,
                       biodiv_richness = biodiv_richness_water_reservoir,
```

```
                        var_CV = var_CV, n_years = n_years)


water_reservoir_yield <- certification_impact_water_reservoir$yield
water_reservoir_cost <- certification_impact_water_reservoir$cost
water_reservoir_risk_increase <- certification_impact_water_reservoir$risk_increase
water_reservoir_risk_reduction <- certification_impact_water_reservoir$risk_reduction
water_reservoir_adaptation <- certification_impact_water_reservoir$adaptation
water_reservoir_mitigation <- certification_impact_water_reservoir$mitigation
water_reservoir_ecology <- certification_impact_water_reservoir$ecology

# Intervention 6: Anti-evapotranspiration sprays ####
certification_impact_a_evap_trans_spray <-
  certification_impact(cost_measure = cost_a_evap_trans_spray,
                       yield_benefit = 0,
                       additional_benefits = 0,
                       event_risk = dry_spells_risk,
                       normal_damage = normal_dry_spell_damage,
                       reduction_damage_measure = a_evap_trans_spray_water_deficit_reduction,
                       # second risk (risk caused by measure)
                       negative_risk_event_measure = 0,
                       normal_damage_not_from_measure = 0,
                       increase_damage_by_measure = 0,
                       mitigation_factors = 0,
                       # ecological impacts
                       soil_quality = 0,
                       water_quality = water_quality_a_evap_trans_spray,
                       biodiv_richness = biodiv_richness_a_evap_trans_spray,
                       var_CV = var_CV, n_years = n_years)


a_evap_trans_spray_yield <- certification_impact_a_evap_trans_spray$yield
a_evap_trans_spray_cost <- certification_impact_a_evap_trans_spray$cost
a_evap_trans_spray_risk_increase <- certification_impact_a_evap_trans_spray$risk_increase
a_evap_trans_spray_risk_reduction <- certification_impact_a_evap_trans_spray$risk_reduction
a_evap_trans_spray_adaptation <- certification_impact_a_evap_trans_spray$adaptation
a_evap_trans_spray_mitigation <- certification_impact_a_evap_trans_spray$mitigation
a_evap_trans_spray_ecology <- certification_impact_a_evap_trans_spray$ecology


# Intervention 7: Irrigation methods ####
certification_impact_irrigation_methods <-
  certification_impact(cost_measure = cost_irrigation_methods,
                       yield_benefit = 0,
                       additional_benefits = 0,
                       event_risk = dry_spells_risk,
                       normal_damage = normal_dry_spell_damage,
                       reduction_damage_measure = irrigation_methods_water_deficit_reduction,
                       # second risk (risk caused by measure)
                       negative_risk_event_measure = 0,
                       normal_damage_not_from_measure = 0,
                       increase_damage_by_measure = 0,
                       mitigation_factors = 0,
                       # ecological impacts
                       soil_quality = soil_quality_irrigation_methods,
                       water_quality = water_quality_irrigation_methods,
```

```
                        biodiv_richness = biodiv_richness_irrigation_methods,
                        var_CV = var_CV, n_years = n_years)


irrigation_methods_yield <- certification_impact_irrigation_methods$yield
irrigation_methods_cost <- certification_impact_irrigation_methods$cost
irrigation_methods_risk_increase <- certification_impact_irrigation_methods$risk_increase
irrigation_methods_risk_reduction <- certification_impact_irrigation_methods$risk_reduction
irrigation_methods_adaptation <- certification_impact_irrigation_methods$adaptation
irrigation_methods_mitigation <- certification_impact_irrigation_methods$mitigation
irrigation_methods_ecology <- certification_impact_irrigation_methods$ecology

# Intervention 8: Irrigation scheduling ####
certification_impact_irrigation_scheduling <-
  certification_impact(cost_measure = cost_irrigation_scheduling,
                        yield_benefit = 0,
                        additional_benefits = 0,
                        event_risk = dry_spells_risk,
                        normal_damage = normal_dry_spell_damage,
                        reduction_damage_measure = irrigation_scheduling_water_deficit_reduction,
                        # second risk (risk caused by measure)
                        negative_risk_event_measure = 0,
                        normal_damage_not_from_measure = 0,
                        increase_damage_by_measure = 0,
                        mitigation_factors = 0,
                        # ecological impacts
                        soil_quality = soil_quality_irrigation_scheduling,
                        water_quality = water_quality_irrigation_scheduling,
                        biodiv_richness = biodiv_richness_irrigation_scheduling,
                        var_CV = var_CV, n_years = n_years)


irrigation_scheduling_yield <- certification_impact_irrigation_scheduling$yield
irrigation_scheduling_cost <- certification_impact_irrigation_scheduling$cost
irrigation_scheduling_risk_increase <- certification_impact_irrigation_scheduling$risk_increase
irrigation_scheduling_risk_reduction <- certification_impact_irrigation_scheduling$risk_reduction
irrigation_scheduling_adaptation <- certification_impact_irrigation_scheduling$adaptation
irrigation_scheduling_mitigation <- certification_impact_irrigation_scheduling$mitigation
irrigation_scheduling_ecology <- certification_impact_irrigation_scheduling$ecology

# Intervention 9: Drainage management  ####
certification_impact_drainage <-
  certification_impact(cost_measure = cost_drainage_mgmt,
                        yield_benefit = 0,
                        additional_benefits = 0,
                        event_risk = flood_event_risk,
                        normal_damage = normal_waterlog_damage,
                        reduction_damage_measure = reduction_waterlog_drainage_mgmt,
                        # second risk (risk caused by measure)
                        negative_risk_event_measure = 0,
                        normal_damage_not_from_measure = 0,
                        increase_damage_by_measure = 0,
                        mitigation_factors = 0,
                        # ecological impacts
                        soil_quality = soil_quality_drainage_mgmt,
                        water_quality = water_quality_drainage_mgmt,
```

```
                       biodiv_richness = biodiv_richness_drainage_mgmt,
                       var_CV = var_CV, n_years = n_years)

drainage_yield <- certification_impact_drainage$yield
drainage_cost <- certification_impact_drainage$cost
drainage_risk_increase <- certification_impact_drainage$risk_increase
drainage_risk_reduction <- certification_impact_drainage$risk_reduction
drainage_adaptation <- certification_impact_drainage$adaptation
drainage_mitigation <- certification_impact_drainage$mitigation
drainage_ecology <- certification_impact_drainage$ecology


# Intervention 10: Composting  ####
composting_adaptation_impact <-
  certification_impact(cost_measure = cost_composting,
                       #yield can increase up to 30% with chemicals in compost
                       yield_benefit = yield_increase_composting,
                       additional_benefits = fertilizer_reduction_composting,
                       event_risk = 0,
                       normal_damage = 0,
                       reduction_damage_measure = 0,
                       # second risk (risk caused by measure)
                       negative_risk_event_measure = 0,
                       normal_damage_not_from_measure = 0,
                       increase_damage_by_measure = 0,
                       mitigation_factors = reduced_chemical_residue_composting +
                         # not a linear relationship, demand may decrease
                         # and production will still continue
                         # here we assume that the relationship is linear
                         reduced_fertilizer_production_composting,
                       # ecological impacts
                       soil_quality = soil_quality_composting,
                       water_quality = water_quality_composting,
                       biodiv_richness = biodiv_richness_composting,
                       var_CV = var_CV, n_years = n_years)

composting_yield <- composting_adaptation_impact$yield
composting_cost <- composting_adaptation_impact$cost
composting_risk_increase <- composting_adaptation_impact$risk_increase
composting_risk_reduction <- composting_adaptation_impact$risk_reduction
composting_adaptation <- composting_adaptation_impact$adaptation
composting_mitigation <- composting_adaptation_impact$mitigation
composting_ecology <- composting_adaptation_impact$ecology


# Intervention 11: Nutrient management with soil analysis ####
nutrient_mgmt_adaptation_impact <-
  certification_impact(cost_measure = cost_nutrient_mgmt,
                       yield_benefit = yield_increase_nutrient_mgmt,
                       additional_benefits = fertilizer_reduction_nutrient_mgmt,
                       # this refers to pests and disease
                       event_risk = pest_outbreak_risk,
                       normal_damage = normal_damage_pests,
                       reduction_damage_measure = reduction_damage_pest_nutrient_mgmt,
                       # second risk (risk caused by measure)
                       negative_risk_event_measure = 0,
```

```
                        normal_damage_not_from_measure = 0,
                        increase_damage_by_measure = 0,
                        mitigation_factors = reduced_chemical_residue_nutrient_mgmt +
                          reduced_fertilizer_production_nutrient_mgmt,
                        # ecological impacts
                        soil_quality = soil_quality_nutrient_mgmt,
                        water_quality = water_quality_nutrient_mgmt,
                        biodiv_richness = biodiv_richness_nutrient_mgmt,
                        var_CV = var_CV, n_years = n_years)

nutrient_mgmt_yield <- nutrient_mgmt_adaptation_impact$yield
nutrient_mgmt_cost <- nutrient_mgmt_adaptation_impact$cost
nutrient_mgmt_risk_increase <- nutrient_mgmt_adaptation_impact$risk_increase
nutrient_mgmt_risk_reduction <- nutrient_mgmt_adaptation_impact$risk_reduction
nutrient_mgmt_adaptation <- nutrient_mgmt_adaptation_impact$adaptation
nutrient_mgmt_mitigation <- nutrient_mgmt_adaptation_impact$mitigation
nutrient_mgmt_ecology <- nutrient_mgmt_adaptation_impact$ecology


# Intervention 12: IPM practices ####
# we assume that the reduction in the outbreak risk by using ipm is
# directly transferred to yield increase in the same rate
ipm_adaptation_impact <-
  certification_impact(cost_measure = cost_ipm_practice,
                        yield_benefit = 0,
                        additional_benefits = pesticide_reduction_ipm_practice,
                        event_risk = pest_outbreak_risk,
                        normal_damage = normal_damage_pests,
                        reduction_damage_measure = reduction_damage_ipm_practice,
                        # second risk (risk caused by measure)
                        negative_risk_event_measure = 0,
                        normal_damage_not_from_measure = 0,
                        increase_damage_by_measure = 0,
                        mitigation_factors = reduced_pesticide_production_ipm_practice,
                        # ecological impacts
                        soil_quality = soil_quality_ipm_practice,
                        water_quality = water_quality_ipm_practice,
                        biodiv_richness = biodiv_richness_ipm_practice,
                        var_CV = var_CV, n_years = n_years)


ipm_practice_yield <- ipm_adaptation_impact$yield
ipm_practice_cost <- ipm_adaptation_impact$cost
ipm_practice_risk_increase <- ipm_adaptation_impact$risk_increase
ipm_practice_risk_reduction <- ipm_adaptation_impact$risk_reduction
ipm_practice_adaptation <- ipm_adaptation_impact$adaptation
ipm_practice_mitigation <- ipm_adaptation_impact$mitigation
ipm_practice_ecology <- ipm_adaptation_impact$ecology

# Intervention 13: Reincorporation of residues  ####
reincorporation_adaptation_impact <-
  certification_impact(cost_measure = cost_reincorporation,
                        yield_benefit = yield_reincorporation,
                        #mulches cover about 60% of ground
                        additional_benefits = herbicide_reduction_reincorporation +
                          fertilizer_reduction_reincorporation,
```

```r
                      event_risk = 0,
                      normal_damage = 0,
                      reduction_damage_measure = 0,
                      # second risk (risk caused by measure)
                      negative_risk_event_measure = 0,
                      normal_damage_not_from_measure = 0,
                      increase_damage_by_measure = 0,
                      mitigation_factors = reduced_herbicide_production_reincorporation,
                      # ecological impacts
                      soil_quality = soil_quality_reincorporation,
                      water_quality = water_quality_reincorporation,
                      biodiv_richness = biodiv_richness_reincorporation,
                      var_CV = var_CV, n_years = n_years)

reincorporation_yield <- reincorporation_adaptation_impact$yield
reincorporation_cost <- reincorporation_adaptation_impact$cost
reincorporation_risk_increase <- reincorporation_adaptation_impact$risk_increase
reincorporation_risk_reduction <- reincorporation_adaptation_impact$risk_reduction
reincorporation_adaptation <- reincorporation_adaptation_impact$adaptation
reincorporation_mitigation <- reincorporation_adaptation_impact$mitigation
reincorporation_ecology <- reincorporation_adaptation_impact$ecology


# Intervention 14: Cover crop ####
cover_crop_adaptation_impact <-
  certification_impact(cost_measure = cost_cover_crop,
                      yield_benefit = 0,
                      additional_benefits = herbicide_reduction_cover_crop,
                      event_risk = 0,
                      normal_damage = 0,
                      reduction_damage_measure = 0,
                      # second risk (risk caused by measure)
                      negative_risk_event_measure = competition_risk,
                      normal_damage_not_from_measure = normal_competition_damage,
                      increase_damage_by_measure = increased_damage_by_competition,
                      mitigation_factors = reduced_herbicide_production_cover_crop,
                      # ecological impacts
                      soil_quality = soil_quality_cover_crop,
                      water_quality = water_quality_cover_crop,
                      biodiv_richness = biodiv_richness_cover_crop,
                      var_CV = var_CV, n_years = n_years)


cover_crop_yield <- cover_crop_adaptation_impact$yield
cover_crop_cost <- cover_crop_adaptation_impact$cost
cover_crop_risk_increase <- cover_crop_adaptation_impact$risk_increase
cover_crop_risk_reduction <- cover_crop_adaptation_impact$risk_reduction
cover_crop_adaptation <- cover_crop_adaptation_impact$adaptation
cover_crop_mitigation <- cover_crop_adaptation_impact$mitigation
cover_crop_ecology <- cover_crop_adaptation_impact$ecology


# Intervention 15: Buffer zone ####
# 100m maximum width of Buffer zone. The maximum area is 5% of the area
certification_impact_buffer <-
  certification_impact(cost_measure = cost_buffer,
```

```
                      # could be timber harvests and other benefits
                      yield_benefit = 0,
                      additional_benefits = -yield_lost_for_buffer,
                      # winds and storms are frequent
                      event_risk = wind_event_risk,
                      normal_damage = normal_wind_damage,
                      reduction_damage_measure = reduction_wind_damage_buffer,
                      # second risk (risk caused by measure)
                      negative_risk_event_measure = 0,
                      normal_damage_not_from_measure = 0,
                      increase_damage_by_measure = 0,
                      mitigation_factors = 0,
                      # ecological impacts
                      soil_quality = soil_quality_buffer,
                      water_quality = water_quality_buffer,
                      biodiv_richness = biodiv_richness_buffer,
                      var_CV = var_CV, n_years = n_years)


buffer_yield <- certification_impact_buffer$yield
buffer_cost <- certification_impact_buffer$cost
buffer_risk_increase <- certification_impact_buffer$risk_increase
buffer_risk_reduction <- certification_impact_buffer$risk_reduction
buffer_adaptation <- certification_impact_buffer$adaptation
buffer_mitigation <- certification_impact_buffer$mitigation
buffer_ecology <- certification_impact_buffer$ecology


# Intervention 16: Conversion of unproductive area ####
certification_impact_conversion <-
  certification_impact(cost_measure = cost_conversion,
                      # i.e. transform to agroforestry with bananas
                      yield_benefit = yield_conversion,
                      #all the other crops/timber that harvested
                      additional_benefits = added_benefit_conversion,
                      event_risk = 0,
                      normal_damage = 0,
                      reduction_damage_measure = 0,
                      # second risk (risk caused by measure)
                      negative_risk_event_measure = 0,
                      normal_damage_not_from_measure = 0,
                      increase_damage_by_measure = 0,
                      mitigation_factors = 0,
                      # ecological impacts
                      soil_quality = soil_quality_conversion,
                      water_quality = 0,
                      biodiv_richness = biodiv_richness_conversion,
                      var_CV = var_CV, n_years = n_years)


conversion_yield <- certification_impact_conversion$yield
conversion_cost <- certification_impact_conversion$cost
conversion_risk_increase <- certification_impact_conversion$risk_increase
conversion_risk_reduction <- certification_impact_conversion$risk_reduction
conversion_adaptation <- certification_impact_conversion$adaptation
conversion_mitigation <- certification_impact_conversion$mitigation
```

```r
conversion_ecology <- certification_impact_conversion$ecology


# Intervention 17: Recycling plastic ####
certification_impact_recycling <-
  certification_impact(cost_measure = recycling_cost,
                       yield_benefit = 0,
                       additional_benefits = 0,
                       event_risk = 0,
                       normal_damage = 0,
                       reduction_damage_measure = 0,
                       # second risk (risk caused by measure)
                       negative_risk_event_measure = 0,
                       normal_damage_not_from_measure = 0,
                       increase_damage_by_measure = 0,
                       mitigation_factors = reduced_plastic_production_recycling,
                       # ecological impacts
                       soil_quality = 0,
                       water_quality = 0,
                       biodiv_richness = biodiv_richness_recycling,
                       var_CV = var_CV, n_years = n_years)

recycling_yield <- certification_impact_recycling$yield
recycling_cost <- certification_impact_recycling$cost
recycling_risk_increase <- certification_impact_recycling$risk_increase
recycling_risk_reduction <- certification_impact_recycling$risk_reduction
recycling_adaptation <- certification_impact_recycling$adaptation
recycling_mitigation <- certification_impact_recycling$mitigation
recycling_ecology <- certification_impact_recycling$ecology


# Intervention 18: Waste disposal plan ####
certification_impact_waste_plan <-
  certification_impact(cost_measure = waste_plan_cost,
                       yield_benefit = 0,
                       additional_benefits = 0,
                       event_risk = 0,
                       normal_damage = 0,
                       reduction_damage_measure = 0,
                       # second risk (risk caused by measure)
                       negative_risk_event_measure = 0,
                       normal_damage_not_from_measure = 0,
                       increase_damage_by_measure = 0,
                       # This can have some mitigation effect but not major
                       mitigation_factors = 0,
                       # ecological impacts
                       soil_quality = 0,
                       water_quality = 0,
                       biodiv_richness = biodiv_richness_waste_plan,
                       var_CV = var_CV, n_years = n_years)

waste_plan_yield <- certification_impact_waste_plan$yield
waste_plan_cost <- certification_impact_waste_plan$cost
waste_plan_risk_increase <- certification_impact_waste_plan$risk_increase
waste_plan_risk_reduction <- certification_impact_waste_plan$risk_reduction
waste_plan_adaptation <- certification_impact_waste_plan$adaptation
```

```r
waste_plan_mitigation <- certification_impact_waste_plan$mitigation
waste_plan_ecology <- certification_impact_waste_plan$ecology


# Intervention 19: Reduce plastic use ####
# here we assume there is a cost of replacing plastics with other materials
# impregnated plastic bags are used for fungicide application
# using a fitted bag for the banana fruit rather than a bag that is too big
plastic_reduction_adaptation_impact <-
  certification_impact(cost_measure = costs_plastic_wrapping_time,
                       yield_benefit = 0,
                       additional_benefits = savings_reduced_plastic,
                       event_risk = 0,
                       normal_damage = 0,
                       reduction_damage_measure = 0,
                       # second risk (risk caused by measure)
                       negative_risk_event_measure = 0,
                       normal_damage_not_from_measure = 0,
                       increase_damage_by_measure = 0,
                       mitigation_factors = reduced_plastic_production_replacement,
                       # ecological impacts
                       soil_quality = 0,
                       water_quality = 0,
                       biodiv_richness = biodiv_richness_reduced_plastic,
                       var_CV = var_CV, n_years = n_years)

plastic_reduction_yield <- plastic_reduction_adaptation_impact$yield
plastic_reduction_cost <- plastic_reduction_adaptation_impact$cost
plastic_reduction_risk_increase <- plastic_reduction_adaptation_impact$risk_increase
plastic_reduction_risk_reduction <- plastic_reduction_adaptation_impact$risk_reduction
plastic_reduction_adaptation <- plastic_reduction_adaptation_impact$adaptation
plastic_reduction_mitigation <- plastic_reduction_adaptation_impact$mitigation
plastic_reduction_ecology <- plastic_reduction_adaptation_impact$ecology

# Intervention 20: Re-use plastic use ####
# here we assume there is a cost of replacing plastics with other materials
# re-using the bags for fungicide application
plastic_reuse_adaptation_impact <-
  certification_impact(cost_measure = costs_plastic_reuse,
                       yield_benefit = 0,
                       additional_benefits = savings_plastic_reuse,
                       event_risk = 0,
                       normal_damage = 0,
                       reduction_damage_measure = 0,
                       # second risk (risk caused by measure)
                       negative_risk_event_measure = 0,
                       normal_damage_not_from_measure = 0,
                       increase_damage_by_measure = 0,
                       mitigation_factors = reduced_plastic_production_plastic_reuse,
                       # ecological impacts
                       soil_quality = 0,
                       water_quality = 0,
                       biodiv_richness = biodiv_richness_reuse_plastic,
                       var_CV = var_CV, n_years = n_years)

plastic_reuse_yield <- plastic_reuse_adaptation_impact$yield
```

```
plastic_reuse_cost <- plastic_reuse_adaptation_impact$cost
plastic_reuse_risk_increase <- plastic_reuse_adaptation_impact$risk_increase
plastic_reuse_risk_reduction <- plastic_reuse_adaptation_impact$risk_reduction
plastic_reuse_adaptation <- plastic_reuse_adaptation_impact$adaptation
plastic_reuse_mitigation <- plastic_reuse_adaptation_impact$mitigation
plastic_reuse_ecology <- plastic_reuse_adaptation_impact$ecology

return(list(energy_use_plan_yield = energy_use_plan_yield,
            energy_use_plan_cost = energy_use_plan_cost,
            energy_use_plan_risk_increase = energy_use_plan_risk_increase,
            energy_use_plan_risk_reduction = energy_use_plan_risk_reduction,
            energy_use_plan_adaptation = energy_use_plan_adaptation,
            energy_use_plan_mitigation = energy_use_plan_mitigation,
            energy_use_plan_ecology = energy_use_plan_ecology,

            energy_equipment_yield = energy_equipment_yield,
            energy_equipment_cost = energy_equipment_cost,
            energy_equipment_risk_increase = energy_equipment_risk_increase,
            energy_equipment_risk_reduction = energy_equipment_risk_reduction,
            energy_equipment_adaptation = energy_equipment_adaptation,
            energy_equipment_mitigation = energy_equipment_mitigation,
            energy_equipment_ecology = energy_equipment_ecology,

            solar_energy_yield = solar_energy_yield,
            solar_energy_cost = solar_energy_cost,
            solar_energy_risk_increase = solar_energy_risk_increase,
            solar_energy_risk_reduction = solar_energy_risk_reduction,
            solar_energy_adaptation = solar_energy_adaptation,
            solar_energy_mitigation = solar_energy_mitigation,
            solar_energy_ecology = solar_energy_ecology,

            other_energy_yield = other_energy_yield,
            other_energy_cost = other_energy_cost,
            other_energy_risk_increase = other_energy_risk_increase,
            other_energy_risk_reduction = other_energy_risk_reduction,
            other_energy_adaptation = other_energy_adaptation,
            other_energy_mitigation = other_energy_mitigation,
            other_energy_ecology = other_energy_ecology,

            waste_water_yield = waste_water_yield,
            waste_water_cost = waste_water_cost,
            waste_water_risk_increase = waste_water_risk_increase,
            waste_water_risk_reduction = waste_water_risk_reduction,
            waste_water_adaptation = waste_water_adaptation,
            waste_water_mitigation = waste_water_mitigation,
            waste_water_ecology = waste_water_ecology,

            water_reservoir_yield = water_reservoir_yield,
            water_reservoir_cost = water_reservoir_cost,
            water_reservoir_risk_increase = water_reservoir_risk_increase,
            water_reservoir_risk_reduction = water_reservoir_risk_reduction,
            water_reservoir_adaptation = water_reservoir_adaptation,
            water_reservoir_mitigation = water_reservoir_mitigation,
            water_reservoir_ecology = water_reservoir_ecology,

            a_evap_trans_spray_yield = a_evap_trans_spray_yield,
```

```
            a_evap_trans_spray_cost = a_evap_trans_spray_cost,
            a_evap_trans_spray_risk_increase = a_evap_trans_spray_risk_increase,
            a_evap_trans_spray_risk_reduction = a_evap_trans_spray_risk_reduction,
            a_evap_trans_spray_adaptation = a_evap_trans_spray_adaptation,
            a_evap_trans_spray_mitigation = a_evap_trans_spray_mitigation,
            a_evap_trans_spray_ecology = a_evap_trans_spray_ecology,

            irrigation_methods_yield = irrigation_methods_yield,
            irrigation_methods_cost = irrigation_methods_cost,
            irrigation_methods_risk_increase = irrigation_methods_risk_increase,
            irrigation_methods_risk_reduction = irrigation_methods_risk_reduction,
            irrigation_methods_adaptation = irrigation_methods_adaptation,
            irrigation_methods_mitigation = irrigation_methods_mitigation,
            irrigation_methods_ecology = irrigation_methods_ecology,

            irrigation_scheduling_yield = irrigation_scheduling_yield,
            irrigation_scheduling_cost = irrigation_scheduling_cost,
            irrigation_scheduling_risk_increase = irrigation_scheduling_risk_increase,
            irrigation_scheduling_risk_reduction = irrigation_scheduling_risk_reduction,
            irrigation_scheduling_adaptation = irrigation_scheduling_adaptation,
            irrigation_scheduling_mitigation = irrigation_scheduling_mitigation,
            irrigation_scheduling_ecology = irrigation_scheduling_ecology,

            drainage_yield = drainage_yield,
            drainage_cost = drainage_cost,
            drainage_risk_increase = drainage_risk_increase,
            drainage_risk_reduction = drainage_risk_reduction,
            drainage_adaptation = drainage_adaptation,
            drainage_mitigation = drainage_mitigation,
            drainage_ecology = drainage_ecology,

            composting_yield = composting_yield,
            composting_cost = composting_cost,
            composting_risk_increase = composting_risk_increase,
            composting_risk_reduction = composting_risk_reduction,
            composting_adaptation = composting_adaptation,
            composting_mitigation = composting_mitigation,
            composting_ecology = composting_ecology,

            nutrient_mgmt_yield = nutrient_mgmt_yield,
            nutrient_mgmt_cost = nutrient_mgmt_cost,
            nutrient_mgmt_risk_increase = nutrient_mgmt_risk_increase,
            nutrient_mgmt_risk_reduction = nutrient_mgmt_risk_reduction,
            nutrient_mgmt_adaptation = nutrient_mgmt_adaptation,
            nutrient_mgmt_mitigation = nutrient_mgmt_mitigation,
            nutrient_mgmt_ecology = nutrient_mgmt_ecology,

            ipm_practice_yield = ipm_practice_yield,
            ipm_practice_cost = ipm_practice_cost,
            ipm_practice_risk_increase = ipm_practice_risk_increase,
            ipm_practice_risk_reduction = ipm_practice_risk_reduction,
            ipm_practice_adaptation = ipm_practice_adaptation,
            ipm_practice_mitigation = ipm_practice_mitigation,
            ipm_practice_ecology = ipm_practice_ecology,

            reincorporation_yield = reincorporation_yield,
```

```
                reincorporation_cost = reincorporation_cost,
                reincorporation_risk_increase = reincorporation_risk_increase,
                reincorporation_risk_reduction = reincorporation_risk_reduction,
                reincorporation_adaptation = reincorporation_adaptation,
                reincorporation_mitigation = reincorporation_mitigation,
                reincorporation_ecology = reincorporation_ecology,

                cover_crop_yield = cover_crop_yield,
                cover_crop_cost = cover_crop_cost,
                cover_crop_risk_increase = cover_crop_risk_increase,
                cover_crop_risk_reduction = cover_crop_risk_reduction,
                cover_crop_adaptation = cover_crop_adaptation,
                cover_crop_mitigation = cover_crop_mitigation,
                cover_crop_ecology = cover_crop_ecology,

                buffer_yield = buffer_yield,
                buffer_cost = buffer_cost,
                buffer_risk_increase = buffer_risk_increase,
                buffer_risk_reduction = buffer_risk_reduction,
                buffer_adaptation = buffer_adaptation,
                buffer_mitigation = buffer_mitigation,
                buffer_ecology = buffer_ecology,

                conversion_yield = conversion_yield,
                conversion_cost = conversion_cost,
                conversion_risk_increase = conversion_risk_increase,
                conversion_risk_reduction = conversion_risk_reduction,
                conversion_adaptation = conversion_adaptation,
                conversion_mitigation = conversion_mitigation,
                conversion_ecology = conversion_ecology,

                recycling_yield = recycling_yield,
                recycling_cost = recycling_cost,
                recycling_risk_increase = recycling_risk_increase,
                recycling_risk_reduction = recycling_risk_reduction,
                recycling_adaptation = recycling_adaptation,
                recycling_mitigation = recycling_mitigation,
                recycling_ecology = recycling_ecology,

                waste_plan_yield = waste_plan_yield,
                waste_plan_cost = waste_plan_cost,
                waste_plan_risk_increase = waste_plan_risk_increase,
                waste_plan_risk_reduction = waste_plan_risk_reduction,
                waste_plan_adaptation = waste_plan_adaptation,
                waste_plan_mitigation = waste_plan_mitigation,
                waste_plan_ecology = waste_plan_ecology,

                plastic_reduction_yield = plastic_reduction_yield,
                plastic_reduction_cost = plastic_reduction_cost,
                plastic_reduction_risk_increase = plastic_reduction_risk_increase,
                plastic_reduction_risk_reduction = plastic_reduction_risk_reduction,
                plastic_reduction_adaptation = plastic_reduction_adaptation,
                plastic_reduction_mitigation = plastic_reduction_mitigation,
                plastic_reduction_ecology = plastic_reduction_ecology,

                plastic_reuse_yield = plastic_reuse_yield,
```

```
                plastic_reuse_cost = plastic_reuse_cost,
                plastic_reuse_risk_increase = plastic_reuse_risk_increase,
                plastic_reuse_risk_reduction = plastic_reuse_risk_reduction,
                plastic_reuse_adaptation = plastic_reuse_adaptation,
                plastic_reuse_mitigation = plastic_reuse_mitigation,
                plastic_reuse_ecology = plastic_reuse_ecology))

}
```

Model inputs

We generated a table of confidence estimates (90%) for use in the decision model. Most variable values are described as a percentage difference from a baseline (in decimals). Others, such as coefficient of variation (coeff. Variation) and ecological values are described as integers.

Table 2: Estimates of inputs provided to the decision model

variable	lower	upper	label
var_CV	5.00	20.000	coeff. Variation
discount_rate	1.00	5.000	Discount rate (%)
n_years	10.00	10.000	Duration of simulation (years)
cost_energy_use_plan	0.01	0.100	Relative increase in production cost due to measure implementation
energy_saved_use_plan	0.02	0.200	Relative energy saved due to measure implementation
increase_efficiency_energy_use_plan	0.02	0.200	Relative increase in energy efficiency due to measure implementation
reduced_fossil_fuel_consumption_energy_use_plan	0.02	0.200	Relative fossil fuel consumption saved due to measure implementation
cost_energy_equipment	0.01	0.200	Relative increase in production cost due to measure implementation
energy_saved_energy_equipment	0.02	0.200	Relative energy saved due to measure implementation
increase_efficiency_energy_equipment	0.02	0.200	Relative increase in energy efficiency due to measure implementation
reduced_fossil_fuel_consumption_energy_equipment	0.02	0.200	Relative fossil fuel consumption saved due to measure implementation
cost_solar_energy	-0.01	0.004	Relative increase in production cost due to measure implementation (this includes the consideration of the initial insallation and offset for the electricity bill)
energy_saved_solar_energy	0.00	0.000	Relative energy saved due to measure implementation
increase_efficiency_solar_energy	0.00	0.000	Relative increase in energy efficiency due to measure implementation
reduced_fossil_fuel_consumption_solar_energy	0.05	0.250	Relative fossil fuel consumption saved due to measure implementation
cost_other_energy	-0.02	-0.004	Relative increase in production cost due to measure implementation (this includes the consideration of the initial insallation and offset for the electricity bill)

variable	lower	upper	label
energy_saved_other_energy	0.0000	0.00	Relative energy saved due to measure implementation
increase_efficiency_other_energy	0.0000	0.00	Relative increase in energy efficiency due to measure implementation
reduced_fossil_fuel_consumption_other_energy	0.2000	0.60	Relative fossil fuel consumption saved due to measure implementation
cost_waste_water_use	0.0100	0.10	Relative increase in production cost due to measure implementation
salinity_risk	0.0500	0.90	Risk of having salinity issues in water
dry_spells_risk	0.0200	0.50	Risk of dry spells
normal_dry_spell_damage	0.2000	0.80	Yield lost to dry spells in a normal year (%)
waste_water_deficit_reduction	0.0100	0.07	Relative decrease in water deficit due to measure implementation
normal_salinity_damage	0.0015	0.07	Normal salinity damage without negative impact of waste water
waste_water_salinity_damage	0.0100	0.10	Yield lost to salinity damage from waste water
soil_quality_waste_water	-10.0000	-1.00	Relative impact of the measure on soil quality
water_quality_waste_water	-5.0000	5.00	Relative impact of the measure on water quality
biodiv_richness_waste_water	0.1000	5.00	Relative impact of the measure on biodiversity richness
cost_water_reservoir	0.0010	0.01	Relative increase in production cost due to measure implementation
reservoir_water_deficit_reduction	0.1000	0.50	Relative decrease in water deficit due to measure implementation
water_quality_water_reservoir	1.0000	5.00	Relative impact of the measure on water quality (reduced groundwater fluctuation)
biodiv_richness_water_reservoir	-10.0000	-1.00	Relative impact of the measure on biodiversity richness
cost_a_evap_trans_spray	0.0010	0.05	Relative increase in production cost due to measure implementation
a_evap_trans_spray_water_deficit_reduction	0.0010	0.02	Relative decrease in water deficit due to measure implementation
water_quality_a_evap_trans_spray	-1.0000	0.10	Relative impact of the measure on water quality (reduced groundwater fluctuation)
biodiv_richness_a_evap_trans_spray	-10.0000	-1.00	Relative impact of the measure on biodiversity richness
cost_irrigation_methods	0.0100	0.20	Relative increase in production cost due to measure implementation
irrigation_methods_water_deficit_reduction	0.5000	0.90	Relative decrease in water deficit due to measure implementation
soil_quality_irrigation_methods	0.1000	5.00	Relative impact of the measure on soil quality
water_quality_irrigation_methods	0.1000	2.00	Relative impact of the measure on water quality
biodiv_richness_irrigation_methods	0.1000	5.00	Relative impact of the measure on biodiversity richness
cost_irrigation_scheduling	0.0010	0.03	Relative increase in production cost due to measure implementation
irrigation_scheduling_water_deficit_reduction	0.1000	0.50	Relative decrease in water deficit due to measure implementation

variable	lower	upper	label
soil_quality_irrigation_scheduling	0.100	2.00	Relative impact of the measure on soil quality
water_quality_irrigation_scheduling	0.100	3.00	Relative impact of the measure on water quality
biodiv_richness_irrigation_scheduling	0.100	2.00	Relative impact of the measure on biodiversity richness
cost_drainage_mgmt	0.001	0.02	Relative increase in production cost due to measure implementation
reduction_waterlog_drainage_mgmt	0.200	0.80	Relative reduction in waterlogging due to measure implementation
flood_event_risk	0.020	0.50	Risk of flood events
normal_waterlog_damage	0.050	0.30	Yield lost to waterlog in a normal year (%)
soil_quality_drainage_mgmt	2.000	7.00	Relative impact of the measure on soil quality
water_quality_drainage_mgmt	0.100	2.00	Relative impact of the measure on water quality
biodiv_richness_drainage_mgmt	2.000	10.00	Relative impact of the measure on biodiversity richness
cost_composting	0.050	0.15	Relative increase in production cost due to measure implementation
yield_increase_composting	0.050	0.55	Relative increase in yield due to measure implementation
fertilizer_reduction_composting	0.100	0.75	Relative reduction in fertilizer use due to measure implementation
reduced_fertilizer_production_composting	0.100	0.75	Relative reduction in fertilizer production due to measure implementation (farm-level responsibility of the CO2 emissions of the production)
reduced_chemical_residue_composting	0.050	0.50	Relative reduction in chemical residues (and N20 emissions) due to measure implementation
soil_quality_composting	1.000	10.00	Relative impact of the measure on soil quality
water_quality_composting	1.000	7.00	Relative impact of the measure on water quality
biodiv_richness_composting	5.000	20.00	Relative impact of the measure on biodiversity richness
cost_nutrient_mgmt	0.050	0.10	Relative increase in production cost due to measure implementation
yield_increase_nutrient_mgmt	0.010	0.40	Relative increase in yield due to measure implementation
fertilizer_reduction_nutrient_mgmt	0.010	0.25	Relative reduction in fertilizer use due to measure implementation
pest_outbreak_risk	0.100	0.30	Risk of pest and disease outbreak (%)
normal_damage_pests	0.100	0.40	Yield lost to pests and disease in a normal year (%)
reduction_damage_pest_nutrient_mgmt	0.100	0.60	Relative reduction in pest and disease damage due to measure implementation
reduced_chemical_residue_nutrient_mgmt	0.100	0.60	Relative reduction in chemical residues (and N20 emissions) due to measure implementation

variable	lower	upper	label
reduced__fertilizer__production__nutrient__mgmt	0.010	0.25	Relative reduction in fertilizer production due to measure implementation (farm-level responsibility of the CO2 emissions of the production)
soil__quality__nutrient__mgmt	1.000	5.00	Relative impact of the measure on soil quality
water__quality__nutrient__mgmt	1.000	7.00	Relative impact of the measure on water quality
biodiv__richness__nutrient__mgmt	1.000	15.00	Relative impact of the measure on biodiversity richness
cost__ipm__practice	0.001	0.05	Relative increase in production cost due to measure implementation
pesticide__reduction__ipm__practice	0.050	0.80	Relative reduction in pesticide use due to measure implementation
reduction__damage__ipm__practice	0.250	0.75	Relative reduction in pest and disease outbreak damage due to measure implementation
reduced__pesticide__production__ipm__practice	0.100	0.75	Relative reduction in pesticide production due to measure implementation (farm-level responsibility of the CO2 emissions of the production)
soil__quality__ipm__practice	0.000	3.00	Relative impact of the measure on soil quality
water__quality__ipm__practice	2.000	9.00	Relative impact of the measure on water quality
biodiv__richness__ipm__practice	1.000	15.00	Relative impact of the measure on biodiversity richness
yield__reincorporation	0.030	0.10	Relative increase in yield due to measure implementation
cost__reincorporation	0.001	0.02	Relative increase in production cost due to measure implementation
herbicide__reduction__reincorporation	0.100	0.50	Relative reduction in herbicide use due to measure implementation
fertilizer__reduction__reincorporation	0.010	0.25	Relative reduction in fertilizer use due to measure implementation
reduced__herbicide__production__reincorporation	0.050	0.30	Relative reduction in herbicide production due to measure implementation (farm-level responsibility of the CO2 emissions of the production)
soil__quality__reincorporation	1.000	8.00	Relative impact of the measure on soil quality
water__quality__reincorporation	1.000	5.00	Relative impact of the measure on water quality
biodiv__richness__reincorporation	1.000	5.00	Relative impact of the measure on biodiversity richness
herbicide__reduction__cover__crop	0.300	0.90	Relative reduction in herbicide use due to measure implementation
yield__reduction__cover__crop	0.001	0.05	Relative reduction in yield due to measure implementation
cost__cover__crop	0.001	0.05	Relative increase in production cost due to measure implementation
reduced__herbicide__production__cover__crop	0.300	0.90	Relative reduction in herbicide production due to measure implementation (farm-level responsibility of the CO2 emissions of the production)

variable	lower	upper	label
competition_risk	0.001	0.01	Risk of cover crop competion with banana for resources (%)
normal_competition_damage	0.001	0.01	Yield lost to competition for resources with other plants in a normal year (%)
increased_damage_by_competition	0.001	0.01	Yield lost to crop competition due to measure implementation
soil_quality_cover_crop	1.000	5.00	Relative impact of the measure on soil quality
water_quality_cover_crop	1.000	10.00	Relative impact of the measure on water quality
biodiv_richness_cover_crop	1.000	10.00	Relative impact of the measure on biodiversity richness
wind_event_risk	0.050	0.30	Risk of wind event (%)
normal_wind_damage	0.100	0.50	Yield lost to wind in a normal year (%)
reduction_wind_damage_buffer	0.100	0.80	Wind damage avoided through measure implementation (%)
yield_lost_for_buffer	0.020	0.08	Relative reduction in yield due to measure implementation (%)
cost_buffer	0.010	0.05	Relative increase in production cost due to measure implementation (%)
soil_quality_buffer	10.000	80.00	Relative impact of the measure on soil quality
water_quality_buffer	20.000	80.00	Relative impact of the measure on water quality
biodiv_richness_buffer	5.000	80.00	Relative impact of the measure on biodiversity richness
yield_conversion	0.010	0.05	Relative increase in yield due to measure implementation (%)
added_benefit_conversion	0.010	0.05	Relative added benefit due to the measure implementation (%)
cost_conversion	0.010	0.05	Relative increase in production cost due to measure implementation (%)
soil_quality_conversion	5.000	10.00	Relative impact of the measure on soil quality
biodiv_richness_conversion	5.000	60.00	Relative impact of the measure on biodiversity richness
recycling_cost	0.010	0.10	Relative increase in production cost due to measure implementation (%)
reduced_plastic_production_recycling	0.300	0.90	Relative reduction in plastic production due to measure implementation (farm-level responsibility of the CO2 emissions of the production)
biodiv_richness_recycling	5.000	50.00	Relative impact of the measure on biodiversity richness
waste_plan_cost	0.010	0.05	Relative increase in production cost due to measure implementation (%)
biodiv_richness_waste_plan	3.000	45.00	Relative impact of the measure on biodiversity richness

variable	lower	upper	label
costs_plastic_wrapping_time	0.01	0.05	Relative increase in production cost due to measure implementation (%)
savings_reduced_plastic	0.01	0.05	Relative decrease in production cost due to measure implementation (%)
reduced_plastic_production_replacement	0.05	0.25	Relative reduction in plastic production due to measure implementation (farm-level responsibility of the CO2 emissions of the production)
biodiv_richness_reduced_plastic	3.00	45.00	Relative impact of the measure on biodiversity richness