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Abstract

CONTEXT

Climate change is challenging vegetable production worldwide. but no study has investigated adaptation at the farm level in the Global North.

OBJECTIVE

We aimed to answer the following questions: (i) How do vegetable farmers perceive climate change and its impacts on farms? (ii) What responses have they already implemented in response to climate change? (iii) What are their adaptation plans for the future? And, (iv) To what extent are adaptation responses and plans related to farm or farmer characteristics?

METHODS

We conducted semi-structured interviews with 17 organic farmers in the Paris region of France. Interview content was processed using qualitative analysis and multiple correspondence analysis.

RESULTS AND CONCLUSION

Vegetable farmers perceived climate change in seasonal patterns (e.g. temperature, frost, wind) and in extreme events (e.g. droughts, heat waves). They related it to negative impacts on (i) vegetables (e.g. increased pressure from arthropods, metabolic disorders, decrease in crop yield and quality), (ii) farm management (e.g. increased and more difficult labour, more complex crop planning), and (iii) profitability (e.g. production losses, increased labour and equipment costs), despite some positive impacts (e.g. potential to extend the growing season or grow tunnel crops outside). Farmers mentioned a wide range of adaptation responses and plans (e.g. cover crops, mulching, agroforestry, diversification, changes in crop planning, equipment to control or mitigate climate conditions in tunnels, efficient irrigation systems). Younger farmers more often expressed the need to acquire knowledge for adaptation plans because they will have to adapt throughout their entire farming career. Although the vegetable area and the age of the farm may have influenced specific adaptation responses, most adaptations that farmers had already implemented did not appear to be related to the farm or farmer characteristics explored. Compared to other types of farming systems in the Global North, vegetable farms may be more exposed and sensitive to climate change but also have more adaptive capacity. Future studies should investigate the influence that vegetable farm characteristics have on their vulnerability compared to those of other types of farming systems in a given soil and climate context.

SIGNIFICANCE

To our knowledge, this is the first study to investigate vegetable farmers' perspectives of adaptations to climate change in Europe. The current study corroborates and enriches studies of the Global South. A preliminary understanding of farmers' perceptions, responses, and plans provides a solid basis for supporting collective action and developing adaptation plans at the regional level.

Key words: horticulture; market gardening; farming system; agroecology; resilience; farming styles

1 Introduction

Climate change is challenging agricultural production worldwide (IPCC, 2019). Vegetable production is no exception, and variations in seasonal patterns or extreme events (e.g. heat waves, droughts, excessive rain, change in seasonal patterns) threaten both yield and quality (Ayyogari et al., 2014; Bisbis et al., 2018; Gruda et al., 2019; Kumari et al., 2018; Scheelbeek et al., 2018). Nicholas and Durham (2012) describe two main research approaches to adaptation to climate change in agriculture: (i) biophysically driven top-down approaches, with production functions such as crop yield as the unit of analysis, and (ii) socially driven bottom-up approaches, which focus on stakeholders as the unit of analysis.

For vegetable production, most biophysically driven studies have performed single-factor laboratory or field experiments and analytically explored management options to adapt a given vegetable crop (e.g. tomato, melon, lettuce) to specific climatic parameters or stresses (Albacete et al., 2014; Altunlu and Gul, 2012; Arbel et al., 2003; Badr et al., 2010; de Cantuário et al., 2021; Hamedi et al., 2022; Kumar et al., 2006; Maraseni et al., 2012). Other studies have used models to simulate the ability of various cropping strategies to maintain yields and improve soil carbon content to adapt to climate change (Deligios et al., 2021; Di Bene et al., 2022). Literature reviews have focused on biophysically driven approaches in studies of physiology, genetics, and agronomy; the behaviour of vegetables under limiting climate conditions; and impacts of climate factors on yield and quality. Potential adaptation responses and research priorities have been drawn from these reviews (Bisbis et al., 2019; Gruda et al., 2019; Kapur, 2013; Koundinya et al., 2017; Singh, 2013).

Although biophysically driven studies are key academic contributions to adaptation, we assume that supporting the (re)design of vegetable farms to adapt to climate change requires a farm-level approach that considers farmers' perceptions and objectives in a specific socio-technical context. One such approach commonly used is the vulnerability perspective, which distinguishes exposure (i.e. being subjected to a detrimental effect), sensitivity (i.e. response to the detrimental effect), and adaptive capacity to climate change (IPCC, 2022, 2001; Polsky et al., 2007; Smit and Pilifosova, 2003). Adaptive capacity is defined as the ability to respond to climate change, including climate variability and extremes, to reduce potential damage, benefit from emerging opportunities, and/or respond to the consequences (IPCC, 2001). Studies of vegetable production that investigate the adaptive capacity of farmers in the face of climate change have been conducted in the Global South, where climate change has been researched for much longer (Arimi, 2021; Asadu et al., 2018; Chepkoech et al., 2020; Gunathilaka and Samarakoon, 2022; Irham et al., 2022; Tekuni Nakuja, 2012). In the Global North (e.g. Europe, USA), many qualitative or mixed studies have explored farmers' perceptions of climate change and adaptation responses, but mainly for cereal crops, livestock production, and winegrowing (e.g. Eakin et al., 2016; Eggers et al., 2015; Gramig et al., 2013; Grothmann and Patt, 2005; Kvalvik et al., 2011; Mitter et al., 2019; Nicholas and Durham, 2012; Wheeler and Lobley, 2021; Zhao et al., 2022). These studies highlight that farmers generally perceive changes in the frequency and intensity of extreme events (e.g. drought, cold, heat, wind) and in seasonal climate patterns (e.g. temperature, rainfall), with potential increased pressure from weeds, diseases, and pests. These changes often challenge farmers, but are also opportunities, especially in the northernmost countries. Farmers can implement a wide range of adaptation responses to these changes, such as growing new species or varieties, changing crop planning, and improving water management. Some of these studies show that farmers' adaptations to climate change depend on characteristics of the farm (e.g. structural factors such as farm size) and farmer (e.g. social variables such as level of education, age, or attitude toward farming) (Eggers et al., 2015; Gramig et al., 2013; Mitter et al., 2019).

To our knowledge, no similar study has yet focused on vegetable production in the Global North, such as in Europe. The present study was designed to help to fill in this knowledge gap. Although vegetable farmers are similar to other types of farmers, certain characteristics of vegetable production may influence their perceptions, adaptation responses, and plans. The study was based on an exploratory case study of the Paris region of France and co-supervised by the regional organic farmers' association (Groupement des Agriculteurs Biologiques Région d'Ile-de-France, www.bioiledefrance.fr), which had observed growing concern about climate change and differing responses to it in its network of organic vegetable farmers. The study's research questions were developed by experts in the association: (i) How do vegetable farmers perceive climate change and its impacts on farms? (ii) What adaptation responses have they already implemented? (iii) What are their adaptation plans for the future? And, (iv) To what extent are adaptation responses and plans related to farm or farmer characteristics ?

We begin by describing the context, methods, and conceptual background of the case study, which was based on qualitative analysis of 17 semi-structured interviews with organic vegetable farmers in the Paris region. We then present the results and discuss them in relation to the literature on adaptations to climate change for vegetable farms and other types of farming systems. We conclude with a research perspective for considering adaptation at the regional level and improving investigation of the vulnerability and adaptive capacity to climate change of vegetable production systems.

2 Case study and methods

2.1 Organic vegetable production and climate change in the Paris region

In studies that focus on the transition of food systems and adaptations to climate change, the urban region, which includes one larger or several smaller urban centre(s) and the surrounding peri-urban and rural areas, is increasingly viewed as a relevant level for planning and governance (Specht et al., 2022; Vaarst et al., 2018). We focused on the Paris region (Figure 1), where the regional government promotes an "agricultural pact" to support more diversified, local production systems that can meet the challenges of climate change (Conseil Régional Ile-de-France, 2018). Nearly half (47%) of the Paris -region is dedicated to agriculture (562,220 ha), most of it arable, of which only 4,500 ha are vegetable crops (DRIAAF Ile-de-France, 2019). Driven by growing consumer demand and environmental and societal health concerns, the percentage of organic production in the region increased by 234% from 2010 to 2019 (GAB Ile-de-France, 2020), and currently ca. 25% of the vegetable area is organic (DRIAAF Ile-de-France, 2019; GAB Ile-de-France, 2020). The regional organic farmers' association initiated the present study to be able to develop targeted R&D or training activities to address vegetable farmers' concerns about climate change.

Climate change is influencing the Paris region: since 1950, its mean annual temperature, currently 11.7°C, has increased by ca. 2°C, and the number of days with frost has decreased by 30%. Since 2015, all summers have been hotter than those from 1950-1975, with record high temperatures (e.g. > 43°C in 2019) and an increase in the frequency and intensity of heatwaves. Its mean rainfall is 720 mm, with a slight trend for an increase in winter and a decrease in summer (GREC Francilien 2022; Institut Paris Région, 2022). See Appendix A.1 for projections of the region's future climate (these projections were realized in a research project after this study and not presented to farmers interviewed).

Figure 1. Location of the Paris region (Ile-de-France) in France (adapted from Superbenjamin (CC BY-SA))

2.2 Conducting semi-structured interviews of farmers

For this initial study, we used an exploratory approach based on semi-structured interviews of vegetable farmers. In 2021, we used "theoretical sampling" (Eisenhardt, 1989; Siggelkow, 2007) to select a wide diversity of farms rather than to ensure statistical representativeness. The organic farmers' association provided a list of 192 farmers in its network who produced organic vegetables, from which 27 were selected by two experts from the association based on seven criteria that they considered relevant to cover the diversity of regional farms. The peer-reviewed and grey literature described these criteria sufficiently well to use them to distinguish vegetable farms and farmers: area of organic vegetable production, total farm utilized agricultural area (UAA), crops produced besides vegetables, gender, age of the farm, age of the farmer, and marketing channels (Chambre d'agriculture de Région Ile-de-France, 2019; Drouet et al., 2020; Morel and

Léger, 2016; Navarrete, 2009; Pépin et al., 2021). Age of the farm equalled the number of years since the farmer began managing the farm (i.e. administrative age); thus, it was a good proxy for farming experience. Experts from the farmers' association also assumed that these characteristics were likely to influence farmers' adaptation responses and plans.

Researchers contacted the 27 farmers by e-mail and/or telephone, and 17 of them agreed to be interviewed, including 3 farmers who also grew non-organic crops (Table 1). Most of the farmers sold vegetables through short (with one intermediary between the farmer and consumers) or direct supply chains, such as in community-supported agriculture (CSA) schemes, in which customers have a contract (often annual) and pay in advance for weekly vegetable boxes. We did not contact other farmers after the 17 interviews, because we decided that we had reached "theoretical saturation" (Eisenhardt, 1989), as no new themes emerged as new interviews were added to the analysis.

All but one farmer (interviewed by telephone) was interviewed on his/her farm, and only one farmer per farm was interviewed. Interviews were organised around four dimensions: (i) context and history of the farm, farming practices, and markets; (ii) perceptions of climate change and its impacts on the farm; (iii) adaptation responses; and (iv) needs and priorities for adapting to climate change in the future. The first pillar was considered an icebreaker to begin the discussion with farmers and provide elements to contextualise their responses, whereas the other three pillars reflected the research questions. Consistent with the method of Olivier de Sardan (2008), the interviewer did not use a questionnaire with pre-written questions, but led an open discussion around the four pillars. This approach fostered spontaneous reactions to farmers' responses, which ensured informal communication to promote high-quality interactions (Beaud and Weber, 2010; Olivier de Sardan, 2008). Interviews followed the European Union's General Data Protection Regulation: farmers were provided a document that explained the context and objectives of the study, how the study data would be managed, and their rights regarding their personal data. After farmers had provided their written consent, interviews lasted 1-3 hours and were audio recorded. Transcripts of these recordings were the data analysed.

Table 1. Description of the 17 organic vegetable farms

Farm	Area of organic vegetable production (ha)	Total UAA (ha)*	Other crops produced**	Gender	Age of the farm (yr)	Age of the farmer (yr)	Marketing channel(s)***
1	1.0	[0.5-5[	No	M	[0-5[	[40-50[	Direct
2	10.0	≥ 100	Field crops	M	≥ 15	[50-60[	Direct; Short
3	0.5	[0.5-5[	Fruit trees	M	[0-5[	[50-60[	Direct
4	2.0	≥ 100	Field crops (including non-organic); Fruit trees	F	[10-15[	[30-40[	Direct
5	8.0	[20-100[	No	M	[0-5[	[40-50[	Direct; Short
6	2.0	[0.5-5[	Fruit trees; Medicinal and aromatic plants	M	[5-10[	[30-40[	Direct
7	4.0	[0.5-5[	Fruit trees	M	[5-10[	[30-40[	Direct; Short
8	2.2	[0.5-5[	Poultry; Fruit trees	M	[0-5[	[40-50[	Direct
9	12.0	[20-100[	Non-organic field crops	F	≥ 15	[40-50[	Direct
10	5.0	[5-20[	Poultry	M	[5-10[	[30-40[	Direct
11	4.5	≥ 100	Non-organic field crops	M	≥ 15	[50-60[	Direct
12	2.5	[0.5-5[	No	M	[5-10[	[30-40[	Direct
13	2.0	[0.5-5[	Fruit trees	M	≥ 15	[50-60[	Direct
14	10.0	≥ 100	Field crops	M	[10-15[	[30-40[	Direct; Short
15	10.0	[5-20[	No	M	≥ 15	[40-50[	Short; Long
16	7.5	[20-100[	Field crops	M	≥ 15	[50-60[	Direct
17	3.0	[0.5-5[	Fruit trees	M	[10-15[	[40-50[	Direct

Sheltered production (cold tunnels) covered 10-20% of the area of organic vegetable production.

*The utilised agricultural area (UAA) included all organic and non-organic production on the farm. **The other crops produced were organic, unless otherwise specified. ***Direct: community-supported agriculture, on-farm sales, and open-air markets; Short: retail sales in local stores, local supermarkets, institutional catering, cooperatives, and restaurants; Long: wholesalers and central purchasing bodies. For the total UAA and age of the farms and farmer, ranges are shown to keep the farms anonymous.

2.3 Conceptual framework

The conceptual framework used to analyse the data was inspired by studies that had adapted the vulnerability perspective to investigate farmers' adaptations to climate change (Kvalvik et al., 2011; Wheeler and Lobley, 2021). We distinguished the following:

- farmers' perceptions of climate change, described as "exposure-sensitivity" by Kvalvik et al. (2011) and as "weather experienced by farmers" by Wheeler and Lobley (2021). Perceived changes were categorised as extreme events or seasonal patterns, which were similar to the categories of "extreme weather" and "more gradual changes" used by Wheeler and Lobley (2021).
- impacts of climate change, which were categorised as positive or negative, as done by Kvalvik et al. (2021) and Wheeler and Lobley (2021).
- farmers' adaptation responses (already implemented) and adaptation plans (in the future), which were similar to the "observed changes" vs. "planned adaptation" of Zhao et al. (2022), the "adaption responses" vs. "plans for adaptation" of Wheeler and Lobley (2021), and the "implemented" vs. "planned or intended" adaptation measures of Mitter et al. (2019).

Farm and farmer characteristics, including farm structure and the age and experience of farmers (Table 1), were considered to be potentially related to adaptation responses and plans, in agreement with the literature (Eggers et al., 2015; Gramig et al., 2013; Mitter et al., 2019). As agronomists using an exploratory perspective, we attempted to relate these factors only to adaptation responses and plans and not to perceptions or other cognitive factors. From an exploratory perspective, the first three categories of the conceptual framework were inductively informed by themes that emerged from qualitative analysis of the interviews. Relations between farm and farmer characteristics and adaptation responses or plans were investigated using multiple correspondence analysis (MCA) and explained using interview responses.

2.4 Qualitative analysis of interviews

The transcripts of the interviews were processed during the qualitative analysis using NVivo software (released in March 2020) and thematic coding (Elo and Kyngäs, 2008; Miles and Huberman, 1984). The first level of coding referred to the categories of the conceptual framework, and a second level of coding summarised the interview content inductively. This second level was initially detailed and similar to the interview content, but increasingly generic themes were gradually created based on iterative cross-analysis of the farmers' interview contents (Eisenhardt, 1989; Yin, 2009). For example, when a farmer mentioned that his tomatoes were burnt by extreme temperatures, the theme was initially coded as "Tomatoes burnt by heat". Throughout the analysis, we observed that other farmers mentioned vegetables burnt by heat; thus, we created a more generic thematic code of "Extreme high temperatures can burn and damage vegetables" (second level of coding), in the category "Negative impacts" (first level of coding). When creating increasingly generic themes in qualitative analysis, the challenge is to determine when to stop. We based this decision on our expertise with vegetable farms and on a compromise between (i) developing enough distinct themes to provide relevant and detailed answers to the research questions and (ii) building only a few themes that were generic enough to apply to all farms in the sample without being overwhelmed by detail. To characterise the impacts of climate change, we distinguished three themes that emerged from farmers' responses: impacts on vegetables, management (i.e. labour organisation and planning), and economics (i.e. sales and costs). The software associated each theme with farmers' quotes, which are cited for illustration using an anonymous code for each farmer (e.g. "F1").

We assumed that themes mentioned spontaneously by more farmers were more relevant; thus, the themes were sorted by the number of farmers who mentioned them. If the same farmer mentioned a given theme several times in the interview, we counted only one occurrence in order to identify the concerns shared by most farmers.

2.5 Multiple correspondence analysis

We performed MCA to investigate relations between adaptation responses (14 themes resulting from the qualitative analysis), adaptation plans (8), and farm and farmer characteristics. MCA projects categorical variables into a few dimensions while maximising the variance to explore relations between categories. We performed the MCA with the *FactoMineR* (Husson et al., 2013; Lê et al., 2008) and *factoextra* (Kassambara and Mundt, 2017) packages of R software (version 4.0.2) (R Core Team, 2020). As MCA inputs, we built a dataset indicating the presence (coded 1) or absence (coded 0) of each adaptation response or plan on each of the 17 farms. Farmer characteristics (Table 1) were included in the MCA as supplementary variables, except for "Gender" and "Marketing channel", as their category responses were unbalanced. Supplementary variables are not used for to building the MCA dimensions. Their projection on the MCA dimensions is realised afterward to explore to the extent they are related to the other variables, which is a classic way of interpreting MCA results (Husson and Josse, 2014). We distinguished two categories of vegetable area associated with contrasting farming structures (i.e. degree of mechanisation and specialisation) according to the grey literature: < 5 ha (10 farms) or ≥ 5 ha (7 farms). For the variable "Other crops produced", farms were assigned the category "Yes" (13 farms) or "No" (4 farms).

We performed three MCA that included (i) only adaptation responses, (ii) only adaptation plans, or (iii) both. As the first and second MCA explained more variance on the two first dimensions (35.4% and 51.9%, respectively) than the third MCA did (33.2%), we considered adaptation responses and plans in two separate MCA. To highlight the most significant relations, we used the dimdesc function of the *FactoMineR* package. One-way analysis of variance (ANOVA) with one factor was performed for each dimension. On each dimension, the coordinates of the individuals (i.e. the 17 farms) were explained by the variables (i.e. adaptation responses, adaptation plans, supplementary variables). An F-test was used to determine whether each variable influenced each dimension, and Student's t-tests were performed for each category. The variables and their categories were sorted by p-value, and only the significant variables ($p < 0.1$) were kept.

Categories whose estimates from the ANOVA had the same sign were related. See Appendices A.2-A.7 for detailed MCA and related dimdesc analyses.

In the body of results section, we only present show the T-tests of the dimdesc analysis for adaptation responses (Table 6) and plans (Table 7).

Results

2.6 Farmers' perceptions of climate change

Farmers perceived climate change as changes in extreme events and in seasonal patterns (Table 2). Extreme events were characterised by their lack of regularity: droughts, heat waves, excessive rain, and extreme wind can occur in the same year. Some farmers said that it was thus more relevant to describe their experience as "climate deregulation" (F9) with "accidents" (F4) rather than as "climate change" (farmers' quotes are in quotation marks, followed by "F" and the farm code in brackets). More intense, frequent, and longer droughts and heat waves were their main concerns. They also perceived that excessive rain occurred more frequently, lasted longer, and caused floods. More extreme wind events (e.g. > 100 km/h) occurred more often and could damage tunnels.

Seasonal patterns were weather factors (e.g. mean temperatures, occurrence of frost, rainfall distribution) that farmers perceived as changing but not as extreme events. The pattern that most farmers mentioned was frost, which they considered to have decreased in frequency and intensity in winter, whereas late frost could still occur in spring. Late frost can damage crops, especially as increasing spring temperatures (in February and March) can enable farmers to plant and sow earlier. Farmers also mentioned more rainfall in winter, although this rain did not benefit vegetables directly but helped refill water reserves. Farmers also mentioned less rain in summer and autumn. Some farmers mentioned that winter and autumn were becoming warmer.

Table 2. Farmers' perceptions of climate change (sorted and coloured by the number of farmers who mentioned each theme)

Type	Description	No. of farmers	Typical quotes
Extreme events	Droughts are becoming more frequent and/or longer, especially in summer	16	"We sometimes have up to five months without rain" (F16). // "We've had summer droughts for four consecutive summers "(F5). // "We have to irrigate more" (F14, F12).
	Heat waves are more frequent and/or longer	9	"Now we have heat waves almost every year, and they're longer" (F12). // "Recently, we had heat waves for three years in a row. This did not happen in the past" (F10).
	Excessive rain has been observed (especially in spring) and causes floods	7	"In 2016, we got so much rain in late May and June that crops were damaged and the soils suffocated" (F11).
	Droughts and heat waves occur simultaneously, which is challenging	5	"For two years in a row, we had droughts with a heat index of 45°C; it's crazy" (F1).
	Extreme winds and storms occur more often and are stronger	5	"We have much more wind than before; now the wind has gone crazy" (F16).
Seasonal patterns	There is less frost in winter (which favours diseases and pests) but still unpredictable late frost in spring	10	"With less frost in winter, pests are becoming worse; they come earlier in the season" (F10). // "Now, we don't know what spring will look like" (F15).
	Rain patterns are changing. In particular, there is more rain in winter (when few crops are growing) and less in summer.	8	"In winter, we have a lot of rain, which isn't useful because we can't water plants with it" (F5). // "Rain doesn't fall anymore in the same periods as before" (F13).
	Spring temperatures vary more within the year (e.g. warm temperatures in early spring followed by frost) and between years	5	"We used to have stable springs. We knew, with a few exceptions, what spring was supposed to look like, but since 2006-2007, we don't know what to do in spring; it can be very warm or not, or very warm at the beginning, and then frost comes" (F15). // "It's very freaky when warm temperatures occur before the risk of frost is over" (F3).
	Autumn and winter are becoming warmer (e.g. fewer extremely low temperatures, less snow, higher mean temperatures)	4	"There's no more winter" (F1, F5). // "Frost happens later in autumn, so we can leave crops in the ground longer" (F10). // "Warmer autumns now allow us to get nice harvests of cabbages, turnips, and radishes" (F2).

2.7 Impacts of climate change on the farm

Farmers perceived that climate change had direct impacts on vegetables and thus on farm management and economics (Table 3). Most impacts mentioned were negative, but farmers also mentioned some positive impacts.

2.7.1 Negative impacts on vegetables

The impact mentioned most frequently was increased pressure of arthropods on vegetables due to higher temperatures, drier conditions, and less frost in winter to regulate their populations. An increase in flea beetles (genus *Phyllotreta*] was the main impact mentioned, as its populations developed faster and earlier, causing substantial damage to vegetables in the *Brassicaceae* family. Farmers also observed more pressure from aphids (e.g. *Aphidius colemani)* and spider mites *(Tetranychus urticae)*. High temperatures encouraged new pests to emerge, such as tomato leafminers (*Tuta absoluta*) which were historically present only in southern France.

Extended periods of high temperatures cause metabolic disorders in vegetables (e.g. going to seed in spring, aborting flowers, having low fertilisation due to decreased activity of natural pollinators). Heat waves also stop the growth of plants, which need a week to recover after them. These factors can result in yield losses. Extremely high temperatures, even when occasional, can burn and damage vegetables, which can decrease the quality of production. None of the farmers had stopped growing a specific crop in response to climate change. However, some farmers said that they may do so in the future, such as no longer growing cabbage due to increased flea beetle pressure, or lettuce in summer given its high water requirements and low resistance to high temperatures.

2.7.2 Negative impacts on farm management

The main impact of climate change on farm management that farmers mentioned related to labour. Climate change increased the need for labour (e.g. to irrigate during droughts, till dry soil, install physical protection against pests, install shade paint and cloths). Climate change also prevented certain operations, such as sowing, if a wet spring caused muddy soil, and spreading manure or destroying cover crops during winter frosts to reduce soil damage. High temperatures and droughts could also make working conditions more difficult: “Plants don’t like to work in heat waves, and neither do farmers” (F7). The climate has become more uncertain, more variable within and between years, and less predictable, which made planning and marketing more difficult. This was a challenge for the farmers, as planning was already complex for diversified vegetable systems that sold through short supply chains. Avoiding extreme events could shorten harvest periods, which caused large problems for products with a short shelf life: “If we get a heat wave, I can decide to harvest all my lettuce at once before they get affected too much, but I then have 72 hours to get rid of 1300 head of lettuce” (F12).

2.7.3 Negative impacts on farm economics

Negative impacts on vegetables (e.g. pest pressure, metabolic disorders, burns, frost) could decrease the yield and quality of harvests, which reduced sales. The need to harvest and sell many vegetables in a single week to adapt to heat waves, when other farmers were doing the same thing, could also reduce sale prices. The increased need for labour and new equipment (e.g. for irrigation or pest management) increased production costs. Altogether, these factors decreased farm profitability.

2.7.4 Positive impacts on vegetables, management, and economics

Warmer temperatures enabled farmers to grow crops outside that used to be grown in tunnels, especially melons and tomatoes. Warmer temperatures also extended the growing season and increased yields in autumn (e.g. for cabbages, turnips, radishes, and beans). Dry conditions in summer could ease weed management if crops had guaranteed access to water but their weeds did not. Dry summers could also enhance the taste of vegetables while increasing their sugar and dry matter contents. One farmer mentioned that less frost in winter made it easier to store root vegetables in the ground, especially carrots, which decreased losses during storage. These positive impacts on vegetable production and management could increase profitability, but no farmer argued that the positive impacts offset the negative impacts.

Table 3. Positive (+) and negative (-) impacts of climate change on the farm vegetables (V) or management (M) (sorted and coloured by the number of farmers who mentioned each theme). Most impacts on vegetables and management had economic consequences, as described in the text.

Impact on	+/-	Description of impacts	No. of farmers	Typical quotes
V	-	Increased pressure of arthropods on vegetables	15	"Due to less frost in winter, insects arrive earlier and stay longer" (F12). // "Some insects love high temperatures" (F2).
M	-	Climate change leads to more labour requirements, prevents certain operations or makes working conditions more difficult	13	"In summer, when it gets too dry, I have to hire a worker only for irrigating" (F15). // "With too much rain, I can't work (F2). // Working during heat waves is exhausting" (F4). // "Without true winter frosts, I can't go into the field to spread horse manure or destroy cover crops without damaging the soil" (F5). // "During heat waves and droughts, we're constantly irrigating and moving irrigation lines (F14).
V	-	Extended high temperatures cause metabolic disorders in vegetables, which decreases production	10	"During heat waves, vegetables simply stop growing" (F17). // "During heat waves, tomato harvests are reduced by two-thirds" (F9).
V	-	Extreme high temperatures (even for a short period) can burn and damage vegetables	9	"The tomatoes and sweet peppers have sunburn" (F10). // L"ettuce doesn't like it when it's too hot; at the end of summer its quality is poor" (F6).
M	-	The climate has become more uncertain and less predictable. Intra- and inter-annual variability makes planning and marketing more difficult.	7	"We've had extreme events, the climate is increasingly chaotic, and there are no more norms or regular seasonal patterns. How can one plan sowing around that?" (F5). // "Last year I had more radishes than I could sell at this time of the year, but this year I haven't harvested any yet" (F11).
V	-	Late frost (after warm temperatures) damages spring vegetables	5	"Once French beans get exposed to frost, it's over" (F11).
V	+	Warmer temperatures allow farmers to grow tunnel crops outside	5	"Now we can grow melons outside" (F14).
V	+	Warmer temperatures allow farmers to extend the growing season and increase production in autumn	3	"Later frost in autumn allows us to grow squash outside until late October" (F2). // "We can now extend the harvest of leafy vegetables by one month in winter, which is a real advantage" (F9).
M	+	Less rain in summer eases weed management	2	Dry conditions in summer decrease weed growth, which is an advantage, if you can irrigate your crops, of course (F10).
V	+	Less rain in summer improves the taste of certain vegetables	2	With less water, some vegetables taste better and have more dry matter (F13). // Melons and squash are sweeter; they're very good (F7).
V	+	Less frost allows farmers to store root vegetables in the ground more easily in winter	1	I used to harvest carrots in December. Now, since we have less extreme frost, I leave them stored in the ground with a wintering veil. It reduces storage losses by 60-70% (F2).

2.8 Adaptation responses

2.8.1 Description of responses

Most of the adaptation responses (Table 4) were based on (i) farming practices, such as diversifying production (variable [Div]), planting trees and shrubs [Trees], selecting adapted varieties [VarietiesR] that can resist droughts or extreme temperatures, growing cover crops [Cover_crops], or mulching and adapted crop planning [Mulching, PlanningR] and (ii) use of equipment to better store and use water [Irrigation], protect crops against pests [Physical_protection], or control climate conditions in tunnels [Equipment]. Two adaptation responses included economic and marketing strategies. Developing CSA box-schemes was mentioned as promoting adaptation to climate change [CSA]. First, customers have a contract (often annual) with farmers and usually pay for vegetable boxes in advance, which helps farmers guarantee income despite extreme events. Secondly, CSA is based on solidarity, and customers are committed to accepting variations in the harvest. Third, CSA enables farmers to interact with customers directly and explain the climate-related challenges they face (i.e. pedagogy and transparency), which makes potential variations in the harvest more acceptable.

Farmers mentioned that adapting to climate change required developing viable business models [Eco] to consider the limited resources available (e.g. water): “Now the question is not to ask, ’OK, I want to produce this much, so how much do I need to irrigate and invest?’, but rather to ask, ‘At a given time I can get 7 m^3 of water per hour and use it 10 hours a day, so what can I grow with it?’” (F3).

2.8.2 Climate change as a new parameter to include in farmers’ multifactorial decision-making

The farmers emphasised that their decision to adopt a given response was usually multifactorial: they considered multiple objectives and not only adaptation to climate change alone. For example, although planting trees and hedges is presented as a climate-change adaptation, farmers noted that planting fruit trees also diversifies production that meets consumer demand for fruit, increases biodiversity, creates a pleasant landscape, and improves working conditions. Similarly, diversifying production or being involved in a CSA box-scheme was primarily aimed at fulfilling marketing, labour, or social objectives, not only adapting to climate change. Farmers also planted cover crops to improve chemical, physical, and biological characteristics of the soil to increase its fertility. Thus, farmers must add climate change as a new parameter to the many other dimensions that they consider when making decisions.

Table 4. Adaptation responses (sorted and coloured by the number of farmers who mentioned each theme)

Code in the MCA	Description	No. of farmers
Div	Diversify production to spread risks and uncertainties (e.g. fruit, new vegetables favoured by a warmer climate)	13
Trees	Plant trees and shrubs (in hedges or agroforestry systems) to create windbreaks and create microclimates, decrease evaporation, buffer temperature variations, and create shade	13
Irrigation	Use more efficient irrigation systems to adapt or mitigate impacts of heat waves and droughts: (i) use precision irrigation equipment such as drip irrigation or soaker hoses, and (ii) store water in tanks to avoid pumping groundwater (collecting water from the roofs of buildings and tunnels)	11
VarietiesR	Use plant varieties that are better adapted to new climate conditions (e.g. more resistant to droughts or high temperatures, go to seed less during warm springs). Some farmers (8) produced their own seeds on-farm (only for certain vegetables) based on heritage varieties to adapt them to local conditions.	11
Cover_crops	Grow cover crops to protect soil from erosion due to extreme events (e.g. strong rain, wind). Only two farmers mentioned that cover crops helped keep water in the soil and could help mitigate drought.	11
Physical_ protection	Use physical protection (e.g. nets, veils) against pests, especially flea beetles	10
Always	Consider that the climate has always changed, and vegetable farmers have always adapted	9
Positive	Benefit from opportunities provided by climate change (e.g. extend growing seasons, grow tunnel crops outside)	9
Equipment	Use equipment to control or mitigate climate conditions (e.g. use shade paint on tunnels or shade cloths). Choose adapted types of tunnels (4), such as double tunnels to increase air circulation, larger tunnels with more temperature inertia, or tunnels with lateral ventilation or light-diffusing plastic (to decrease peak temperatures). Some farmers stated that climate conditions, irrigation, and shading were easier to manage in tunnels (3) and that adaptation to climate change will require increasing the area of tunnels.	8
PlanningR	Adapt crop planning to delay or advance the harvest of certain crops. Doing so requires identifying marketing channels for products that arrive earlier or later in the season.	8
No_modif	Farmers who had not yet modified their practices greatly	8
CSA	Use community-supported agriculture box-schemes	6
Mulching	Use organic (5) or plastic (5) mulch to keep water in the soil and decrease soil temperatures. Mulch cannot be used with crops that are sown (e.g. carrots), and using straw as mulch can attract rodents or slugs, create a source of weeds, and increase labour. Plastic was perceived as a source of negative environmental impacts (e.g. energy consumption, release of plastic particles into ecosystems).	6
Eco	Design business models that consider climate change	4

2.8.3 *Some farmers put the negative impacts of climate change in perspective or saw opportunities*

Some farmers mentioned that vegetable farmers had always adapted to climate conditions, considered uncertainty, and modified their practices in response [Always]; they also doubted that adapting to climate change would be more challenging in the future. As mentioned, others argued that the warmer seasonal patterns caused by climate change could provide opportunities [Positive](see positive impacts in 2.7). ; nevertheless, they were worried about extreme climate-related events. Although they responded to changes in seasonal patterns and extreme events, half of the farmers considered that climate change had not caused them to redesign their practices greatly, perhaps because they were still uncertain or did not yet have enough hindsight on the multiple impacts of climate change.

2.9 Adaptation plans

Farmers expressed the need to acquire theoretical and practical knowledge to develop future adaptation responses tailored to their farm (Table 5). Farmers described their expectations for the training that agricultural advisors could develop, as well as exchanges of practices between farmers, and experiments on the following subjects: adapted varieties [VarietiesP], alternative farming practices (e.g. mulching, reduced tillage) [Farming], soil functioning [Soil], design of agroforestry systems [Agroforestry], vegetable physiology [Physio], pest identification and management [Pest], and adaptation of crop planning [PlanningP] and water management [Water_management].

Some farmers expressed the need for collective organisation to (i) produce and share farm-produced seeds of vegetable varieties that are adapted to climate change and (ii) share certain purchases, especially shade paint for tunnels. Some farmers argued that governments could better support adaptations to climate change, such as through subsidies to plant trees and hedges that create beneficial microclimates or that store carbon in the soil to increase water retention.

Table 5. Adaptation plans (sorted and coloured by the number of farmers who mentioned each theme)

Coding in the MCA	Description	No. of farmers
VarietiesP	Identify or develop vegetable varieties that are more adapted to climate change. Varieties that are already used in warmer climates (e.g. southern France) could be a starting point, but they must be suitable for local conditions and practices. Five farmers believed that seed companies could contribute to this adaptation. Only one farmer indicated that on-farm selection could support adaptation, and desired training on the subject.	8
Farming	Acquire or develop knowledge and experience to implement alternative farming practices (e.g. intercropping (1), growing green manure (3), mulching (1), no-tillage or reduced tillage (3)) that can optimise resource use and retain water in the soil	7
Soil	Gain expertise in soil functioning (e.g. nutrient and water cycles, soil ecology) and use tools to monitor soil conditions (e.g. water and organic matter contents, biological activity) to adopt a more holistic approach to soil that combines multiple alternative practices and organic amendments	7
Agroforestry	Learn about the benefits and limitations of agroforestry and how to design agroforestry systems adapted to the local contexts of vegetable farms	6
Physio	Gain theoretical and practical knowledge about vegetable physiology (e.g. biological cycles, biophysical requirements at each stage) to better adapt practices to climate change.	5
Pests	Gain theoretical knowledge about the identification and functioning (e.g. biological cycles) of pests and how climatic parameters influence them, as well as practical knowledge about establishing farming practices to regulate pest pressures (e.g. plant decoctions, biological control, attracting natural enemies)	5
PlanningP	Gain knowledge about and experience with adapting crop planning to climate change: knowing which vegetables to grow in which period of the year, which vegetables to plant earlier or later, and how to combine different sowing/planting periods to ensure climatic resilience	4
Water_ management	Acquire knowledge about water resource management to optimise or promote more efficient irrigation methods and practices, and collect and store water more efficiently in winter	4

2.10 Relations between adaptation and farm and farmer characteristics

2.10.1 Adaptation responses

Most adaptation responses (8 out of 14) included adapted varieties [VarietiesR], cover crops [Cover_crops], mulching [Mulching], CSA [CSA], adapted crop planning [PlanningR] and business models [Eco], and putting climate change in perspective [Always, Positive] and were not related to the farm or farmer characteristics explored (Table 6). The vegetable area (UAA_veg) and age of the farm (Farm.creation) were related to six adaptation responses on the first MCA dimension. Using physical protection against pests [Physical_protection_1] and planting trees and hedges [Trees_1] were related to a smaller vegetable area and more recently created farms, likely because both are easier and less expensive to develop on smaller areas. Farmers also mentioned that including agroforestry in vegetable systems had been widely discussed in organic networks only recently, which explains why recently created farms tended to include more trees. Farmers with more experience (Farm.creation≥15yr) and larger vegetable area tended to use irrigation systems and equipment more to collect and store water [Irrigation_1]. These farmers perceived optimisation of water resources primarily as way to decrease production costs and increase profitability on larger areas, which consume more water than small areas. As these farms are generally more economically robust, they can invest in water collection and storage equipment more easily. Most farmers with more experience and vegetable area had already diversified production [Div_1] and considered that they had modified their practices significantly to adapt [No_modif_0]. Using equipment to control or mitigate climate conditions ([Equipment_1]) appeared to be related to less vegetable area, but none of the interview content explained this relation.

Farm characteristics were not related to the second MCA dimension, but [Always_1], [PlanningR_1], and [Eco_0] were related to each other, which indicates that farmers who put impacts of climate change in perspective tended to have already adapted by modifying their crop planning. Interview responses showed that due to their confidence in their ability to adapt, they felt no need to change their business model. Putting climate change in perspective was not, however, related to a lack of adaptation responses: interview content showed that farmers who put impacts of climate change in perspective were confident in their ability to adapt to their environment continuously, as they had always done.

Table 6. Relation between adaptation responses, farm and farmer characteristics, and the first two dimensions of the multiple correspondence analysis (MCA). Extract of the analysis using the dimdesc function (Appendix A.4). Student's t-tests were based on one-way ANOVA, which explained the farms' coordinates on the related MCA dimension (Dim) using the categories. Only categories with p < 0.1 were kept. Categories whose estimates have the same sign are related.

Dim	Category	Estimate	p-value
1	Physicalprotection_0	0.37	5.0E-05
	Trees_0	0.40	5.2E-04
	Irrigation_1	0.26	2.0E-02
	Farm.creation≥15yr	0.37	3.3E-02
	UAA_Veg≥5ha	0.20	7.0E-02
	No_modif_0	0.20	7.5E-02
	Div_1	0.22	9.2E-02
	Equipment_0	0.19	9.8E-02
	Equipment_1	-0.19	9.8E-02
	Div_0	-0.22	9.2E-02
	No_modif_1	-0.20	7.5E-02
	UAA_Veg≤5ha	-0.20	7.0E-02
	Irrigation_0	-0.26	2.0E-02
	Trees_1	-0.40	5.2E-04
	Physicalprotection_1	-0.37	5.0E-05
2	Always_0	0.29	8.3E-04
	PlanningR_0	0.26	3.4E-03
	Eco_1	0.20	7.7E-02
	Eco_0	-0.20	7.7E-02
	PlanningR_1	-0.26	3.4E-03
	Always_1	-0.29	8.3E-04

See Table 4 for the codes of adaptation responses (1 means "presence" and 0 means "absence") and Table 1 for supplementary variables. Categories of supplementary variables are shown in bold.

2.10.2 Adaptation plans

Farmer age was the only farm or farmer characteristic related to adaptation plans (Table 7). On the first MCA dimension, the oldest farmers (40-50 years old) tended to lack most types of adaptation plans (6 out of 8), related to water management [Water_management_0], adapted crop planning [PlanningP_0], adapted varieties [VarietiesP_0], vegetable physiology [Physio_0], pest management [Pests_0], and alternative farming practices [Farming_0]. Interviews indicated that older farmers were more confident in their ability to keep their farm going without drastic changes until retirement. In contrast, younger farmers expressed more often the need to develop future adaptation plans and to acquire related knowledge, as they considered that climate change will be central throughout their entire farming career. As one young farmer commented, "I'm a climate change farmer" (F6).

Plans related to agroforestry [Agroforestry] and soil management [Soil] were not related to any farm or farmer characteristics on the first two MCA dimensions, and none of the interview content explained this.

On the second MCA dimension, no farmer characteristics were related to adaptation plans; however, as on the first MCA dimension, adaptation plans tended to be related on the same farms. This was supported by interview content in which farmers did not view adapting to climate change as a single plan but instead as something that will require systemic approaches that combine several adaptation options.

Table 7. Relations between adaptation plans, farm and farmer characteristics, and the first two dimensions of the multiple correspondence analysis (MCA). Extract of the analysis using the dimdesc function (Appendix A.7). Student's t-tests were based on one-way ANOVA that explained the farms' coordinates on the related MCA dimension (Dim) using the categories. Only categories with p < 0.1 were kept. Categories whose estimates have the same sign are related.

Dim	Category	Estimate	p-value
1	Water_management_1	0.58	1.4E-05
	PlanningP_1	0.53	2.5E-04
	VarietiesP_1	0.41	1.3E-03
	Physio_1	0.36	1.6E-02
	Pests=Pests_1	0.32	4.0E-02
	Farming_1	0.28	5.3E-02
	Farming_0	-0.28	5.3E-02
	Pests_0	-0.32	4.0E-02
	Age=40-50yr	-0.42	2.8E-02
	Physio_0	-0.36	1.6E-02
	VarietiesP_0	-0.41	1.3E-03
	PlanningP_0	-0.53	2.5E-04
2	Physio_0	0.33	1.9E-03
	Farming_0	0.25	1.7E-02
	Soil_0	0.22	4.1E-02
	Soil_1	-0.22	4.1E-02
	Farming_1	-0.25	1.7E-02
	Physio_1	-0.33	1.9E-03

See Table 5 for the codes of adaptation plans (1 means "presence" and 0 means "absence") and Table 1 for supplementary variables. Categories of supplementary variables are shown in bold.

3 Discussion

3.1 Corroborating and enriching the literature on adaptation of vegetable farmers

The study shows that in the context of the Global North, vegetable farmers' perceptions of the seasonal patterns and extreme events of climate change (Table 2) are consistent with those in the literature on the Global South (Arimi, 2021; Gunathilaka and Samarakoon, 2022; Tekuni Nakuja, 2012). The interviewed farmers' emphasis on the greater frequency and length of droughts is consistent with the literature that presents droughts as a major challenge for vegetable production (Abewoy, 2018; Bisbis et al., 2019; Keatinge et al., 2014).

Although the literature on the influence of climate change on agriculture usually presents increased variability as a key challenge (Alemayehu and Bewket, 2017; Karki et al., 2020; Obwocha et al., 2022; Reidsma et al., 2010), few studies based on interviews with vegetable farmers have clearly highlighted this issue (Arimi, 2021; Asadu et al., 2018; Irham et al., 2022; Tekuni Nakuja, 2012). The farmers in the present study

were specifically concerned about intra- and inter-annual variability in rainfall, temperature, and the occurrence of frost, which cause uncertainties and difficulties in planning crops and selling produce.
Most negative impacts of climate change that farmers mentioned also corroborate those in the literature (Abewoy, 2018; Arimi, 2021; Ayyogari et al., 2014; Bisbis et al., 2019; Gora et al., 2019; Irham et al., 2022). The interviewed farmers' emphasis on the increased pressure of arthropods confirms that pest pressure is a major challenge of climate change to vegetable farming (Abewoy, 2018; Bisbis et al., 2018; Keatinge et al., 2014). Although general studies of agriculture mention that climate change may increase weed growth (Korres et al., 2016), the present study corroborates studies that focused more on vegetable production, which did not mention specific issues related to weed management (Bisbis et al., 2019; Gruda et al., 2019). Some farmers in the present study mentioned that dry conditions in summer could even help manage weeds as long as irrigation water was available.

The farmers highlighted several positive impacts of climate change on vegetables that are described in the literature, such as the potential to extend the growing season, growing tunnel crops outside, and improved taste (Bisbis et al., 2018). For product quality, some farmers mentioned higher sugar and dry matter contents under certain conditions, but none mentioned the content of other macro- or micro-nutrients, as in the study of Dong et al. (2018). Some studies argue that an increase in atmospheric CO_2 may stimulate photosynthesis and thus increase yields (Gruda et al., 2019; Korres et al., 2016). The farmers we interviewed did not mention this potential increase in yield, as the amount of water, which is threatened by droughts, limits vegetable growth much more than the amount of CO_2 does.
Studies have shown that climate change can increase labour and production costs for vegetable farmers (Arimi, 2021; Tekuni Nakuja, 2012), but they provide few details. The present study shows that the increased need for labour can be related to irrigating during droughts, tilling dry soils, installing physical protection against pests, or installing equipment to provide shade. In contrast, studies in the Global South found that access to investments (e.g. bank loans) is a central concern for smallholders for adapting to climate change. Farmers in the present study did not mention this aspect, but a few of them mentioned that impacts of climate change on income and costs should be considered when designing viable long-term business models. The farmers we interviewed who put impacts of climate change in perspective (as also mentioned by Wheeler and Lobley (2021)) trusted their ability to adapt, as they have always adapted to the weather (as also mentioned by Osborne and Evans (2019), cited by Wheeler and Lobley (2021).
Adaptation responses and plans highlighted in the present study are consistent with those in studies of vegetable farms in the Global South (Arimi, 2021; Asadu et al., 2018; Bisbis et al., 2019, 2018; Gunathilaka and Samarakoon, 2022; Irham et al., 2022; Koundinya et al., 2017; Singh, 2013). However, some responses mentioned in the literature were not mentioned by the farmers interviewed, such as using more pesticides, biotechnology to develop adapted varieties, and climate warning or prediction systems (Arimi, 2021; Irham

et al., 2022; Singh, 2013). Not using pesticides or biotechnology is consistent with the philosophy defended by the organic farmers interviewed.

3.2 Further research perspectives on farm adaptations to climate change

3.2.1 Considering farm characteristics in climate change adaptation

Studies have shown that certain farm and farmer characteristics are positively, negatively, or not related to adaptation to climate change (with contradictory results depending on the context), such as farmer experience (Gunathilaka and Samarakoon 2022; Irham et al. 2022), farmer age (Gunathilaka and Samarakoon, 2022; Tekuni Nakuja, 2012), farmer education (Eggers et al., 2015), farm size (Eggers et al., 2015; Gramig et al., 2013), access to capital (Chepkoech et al., 2020), and attitude toward farming (Mitter et al., 2019). An original aspect of the present study was distinguishing adaptation responses and plans while exploring their relations with farm and farmer characteristics. Although we found some relations (e.g. farmer age was related to most adaptation plans, younger farmers more often expressed the need to acquire knowledge), most adaptation responses, especially putting climate change impacts in perspective, were not related to the farm or farmer characteristics explored. To better understand the variety of adaptation responses among farmers, agronomists could draw on the literature on socio-cognitive processes of risk perception and adaptive response, such as the model of private proactive adaptation to climate change (Grothmann and Patt, 2005).

We found that differences in vegetable area and the age of the farm influenced the emergence of specific adaptation responses, rather than influencing adaptation as a whole. For example, farmers with large vegetable area were more likely to invest in efficient irrigation systems, whereas those with less area were more likely to use agroforestry. Farmers emphasised that their adaptation responses also considered many other constraints or objectives (e.g. economic or environmental), which is consistent with studies that highlight that climate is not the only factor of change and should be considered as an additional parameter in farmers' multifactorial decision-making (Kvalvik et al., 2011; Zhao et al., 2022). In this sense, further exploring adaptation responses as a function of specific farm and farmer characteristics, objectives, and contexts is a promising research avenue.

3.2.2 Analysing and assessing combinations of adaptation responses

The present study confirms the necessity to implement different adaptation responses at the vegetable farm level (Bisbis et al., 2019; Gruda et al., 2019; Kapur, 2013; Koundinya et al., 2017; Singh, 2013). As in other studies, however, we only listed adaptation responses without (i) analysing potential synergies or antagonisms between them in different contexts or (ii) assessing impacts of combinations of them on farm sustainability and resilience. To our knowledge, only a few studies that developed models based on experimental data (Deligios et al., 2021; Di Bene et al., 2022) have quantitatively explored impacts of combining multiple adaptation responses (e.g. cover crops, crop-residue management, rotations). Further research on this subject is required to better support vegetable farmers.

3.2.3 Investigating the role of post-harvest and marketing practices

The farmers we interviewed mentioned that adaptation responses were not only farming practices, but also post-harvest and marketing practices. For example, CSA box-schemes can help buffer climate variability or extreme events. Changes in crop planning and varieties, as well as adding new crops or (fruit) trees depend on the ability to find adequate marketing channels, as observed in other studies (Wheeler and Lobley, 2021). Most organic farmers we interviewed were involved in direct selling, which can be both a constraint, as they need to guarantee a certain diversity and quantity of vegetables throughout the year (Aubry et al., 2011; Morel et al., 2018), and an opportunity, as they can communicate directly with consumers. The literature rarely mentions these market constraints and opportunities, although some of it notes that most vegetables have a short shelf life, which decreases the ability to store them to mitigate variability (Arimi, 2021). This suggests that involving food-chain stakeholders to design coupled innovations (Meynard et al., 2017) in post-harvest management, storage, processing, and marketing could support vegetable farmers while meeting a changing and more variable supply with local demand.

3.3 Vulnerability and adaptive capacity of vegetable farms in the Global North

Vulnerability assessments consider that vulnerability to climate change is a function of the exposure, sensitivity, and adaptive capacity of farmers (IPCC, 2022, 2003, 2001; Polsky et al., 2007; Smit and Pilifosova, 2003). We approached exposure and sensitivity via the concepts of perceptions and impacts of climate change on the farm. Most changes and impacts perceived by vegetable farmers were similar to those highlighted by studies of other types of farming systems in Europe and the USA (Eakin et al., 2016; Kvalvik et al., 2011; Nicholas and Durham, 2012; Wheeler and Lobley, 2021). For adaptive capacity, the adaptation responses and plans of vegetable farmers highlighted in the present study were also consistent with studies of other types of farming systems (Eakin et al., 2016; Kvalvik et al., 2011; Nicholas and Durham, 2012; Wheeler and Lobley, 2021; Zhao et al., 2022). Despite mentioning some positive impacts that represent potential opportunities, vegetable farmers in the Paris region mentioned mainly negative impacts of climate change, which is the opposite of farmers in the northernmost European countries, such as Norway (Kvalvik et al., 2011). To adapt, vegetable farmers in the present study mentioned developing more efficient irrigation and water management strategies as well as tree planting and agroforestry, which Zhao et al. (2022) associated more with southern European countries. Despite being in an Atlantic Coast climate (according to the classification of Zhao et al. (2022)), the vegetable farmers interviewed used these strategies because vegetable crops are generally more sensitive to water stress than other crops, as they are shallow-rooted and contain mainly water (Parkash and Singh, 2020), and are often grown in tunnels or greenhouses, in which the temperature can exceed the outside temperature (Gruda et al., 2019). However, as Gruda et al. (2019) also mention, the vegetable farmers argued that production in tunnels also provides the freedom to adapt while (i) controlling climate conditions (e.g. use of shade paint or cloths, double tunnels to promote air circulation, larger tunnels with higher temperature inertia, tunnels with lateral ventilation, tunnels with light-diffusing plastic) or (ii) using drip irrigation to manage water more efficiently. Although most studies of adaptation to climate change in the Global North mention changes in crop planning (Eakin et al., 2016; Kvalvik et al., 2011; Nicholas and Durham, 2012; Wheeler and Lobley, 2021; Zhao et al., 2022), the short cropping cycle of many vegetable crops may be an advantage for vegetable farmers. Further research should be conducted on vegetable farms in the Global North to investigate the extent to which their characteristics make them more or less adaptable or vulnerable than other types of farming systems in a given soil and climate context. These elements would be crucial for differentiating public support or constraints (e.g. water restriction during droughts) as a function of the farming system.

3.4 Supporting vegetable farmers at the regional level

The only factors beyond the farm level that the farmers mentioned that would facilitate adaptation were subsidies to support tree planting. However, studies highlight the need to foster and plan adaptations to climate change at the municipal or regional level (Alam et al., 2020; Vizinho et al., 2021). The preliminary understanding of farmers' perceptions, adaptation responses, and adaptation plans provided by the present study could be a solid basis on which to develop relevant adaptation measures at the regional level, such as insurance mechanisms to guarantee farmer income when impacted negatively by climate change or ambitious catchment-management plans to guarantee farmers' access to water. The present study confirms farmers' need for better access to knowledge to adapt (Arimi, 2021; Asadu et al., 2018; Eakin et al., 2016; Irham et al., 2022). In this the regard, the regional farmers' association that co-supervised this study was inspired by details of the farmers' adaptation plans, which they plan to use to develop training programs, create informational material (e.g. videos), and promote collective exchanges of practices between farmers.

3.5 Methodological limits and perspectives

3.5.1 Increasing the sample size to improve generality

As the study was based on 17 interviews with organic farmers in the Paris region, the generality of its results on adaptation of vegetable farmers in the Global North could be increased by conducting similar interviews in other contexts, and with non-organic vegetable farmers as well, to explore whether and to what extent their perceptions of climate change and adaptation strategies differ.

3.5.2 Reliability of the MCA

MCA usually explains a lower percentage of variance than principal component analysis or correspondence analysis does because the individuals studied are placed in a multi-dimensional space whose dimensions increase as the number of variables and their categories increase (Husson and Josse, 2014). The percentages of variance explained in the present study are similar to those in many other studies of agricultural systems that used MCA (Choisis et al., 2012; Solano et al., 2000). The approach we used to interpret the MCA (i.e. dimdesc function, ANOVA, $p < 0.1$) is common; thus, the relations between variables that we highlighted can be considered robust. However, we found only a few relations between adaptation responses or plans and farm and farmer characteristics. Including more farms could identify other relations or confirm the absence of relations more robustly.

3.5.3 From farmers' individual perceptions to a collective consensus supported by empirical data

The farmers indicated that their perceptions were based essentially on feelings and observations in the field. Climate projections performed after this study (Appendix A.1) showed that farmers' perceptions of changes in rainfall, temperature, and frost in the Paris region were accurate. However, further and finer analysis of climate data and projections is needed to assess the increased intra- and inter-annual variability that farmers mentioned.

Some of the farmers interviewed were reluctant to make significant changes to their practices without more certainty about climate change, as also observed by Mitter et al. (2019). Most of them explained that they were interested in scientific approaches to deepen their understanding of climate phenomena and their impacts. Because we assumed that the number of farmers who spontaneously mentioned a given theme reflected the theme's relative importance, we may have underestimated the importance of some themes that only a few farmers mentioned. Providing empirical evidence with climate data, projections, and related impacts on vegetable farms is crucial to build a collective consensus in support of further exchange of practices between farmers and research on adaptation involving farmers (Denhartigh, 2014).

4 Conclusion: adaptation beyond the farm level

The results of 17 interviews with organic vegetable farmers in the Paris region generally corroborated those of studies of vegetable farms in the Global South and of other types of farming systems in the Global North. They indicated that farmers (i) perceived climate change in climate patterns and extreme events; (ii) related climate change mainly to negative impacts on vegetables, farm management (especially labour organisation), and profitability, despite perceiving some positive impacts; and (iii) had wide range of adaptation responses and plans. Younger farmers expressed a greater need to acquire knowledge because they will have to adapt throughout their entire farming career. Although the vegetable area and age of the farm may have influenced specific adaptation responses, most adaptations that farmers had already implemented did not appear to be related to the farm or farmer characteristics explored. Improving understanding of the diversity of adaptation responses on organic vegetable farms thus requires further investigation, such as by including more socio-cognitive dimensions and/or more precise analysis of farmers' contexts and objectives.

Compared to other types of farming systems in the Global North, vegetable farms may be more exposed and sensitive to climate change because vegetable crops are particularly sensitive to water stress and involve sheltered production in which temperatures can exceed those outside. They may also have more adaptive capacity because sheltered production increases control of climate parameters and can use efficient irrigation equipment, and vegetable crops have often short cropping cycles, which may ease modification of crop planning. Further research is required to investigate the extent to which the characteristics of vegetable farms make them more or less vulnerable than other types of farming systems in a given soil and climate context. These elements would be crucial for determining public support or constraints at the regional level as a function of the farming system.

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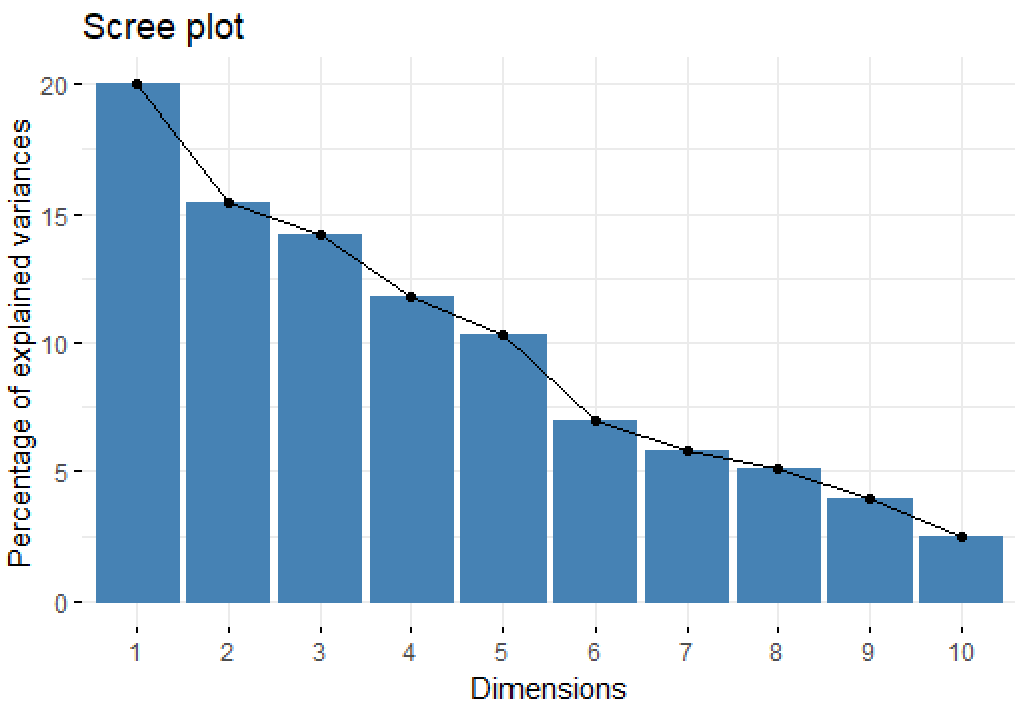
Appendices

A.1 Synthesis of seasonal climate projections in the Paris region in the future (2021-2060) compared to a reference past period (1990-2020), adapted from (Touili et al., 2023, 2022)

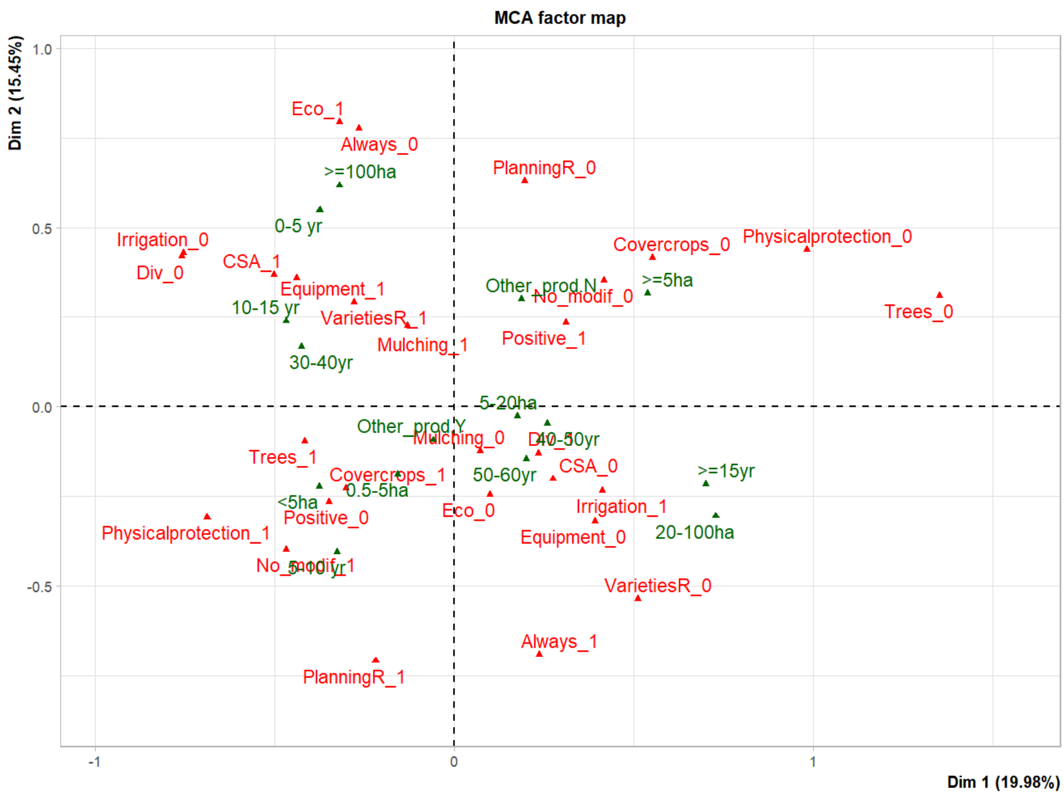
Winter (January-March)	Spring (April-June)	Summer (July-September)	Autumn (October-December)
Temperatures			
Increased minimal and mean temperatures.	Increased minimal, mean and maximal temperatures.	Increased minimal, mean and maximal temperatures. Longer and more frequent heat wave events (with maximal temperatures above 30°C and minimal temperatures above 18°C during at least 3 successive days).	Increased of minimal, mean and maximal temperatures. Higher thermal amplitudes (difference between maximal and minimal daily temperatures).
Frost events			
Less days of frost.	Less days of frost with lasts days of frost occurring earlier in the season (2 weeks earlier in median).		First frost days occurring later in the season (till 1 week later in median).
Precipitation and potential evapotranspiration			
Increased precipitations.	Precipitations globally closed to the reference. However, in the near future, increased of precipitations is possible depending on areas. Increased evapotranspiration.	Decreased precipitations. Increased evapotranspiration.	Precipitations closed to the reference past period. Increased evapotranspiration.
Soil humidity*			
In extreme years (one year out of five) soils become “moderately dry” to “very dry”.	In extreme years (one year out of five) soils become “very dry” to “extremely dry”. In the near future only, soils can also be “moderately humid” in the years with more precipitation in Spring (one year out of five).	In extreme years (one year out of five) soils become “very dry” to “extremely dry”.	In extreme years (one year out of five) soils become “very dry” to “extremely dry”.

*Projections were realized with the regional CLMcom-CCLM4-8-17 model available on the French National climate platform called DRIAS (http://www.drias-climat.fr/) applied to 3 contrasting 8*8km areas of the Paris city-region considering the RCP 4.5 scenario* (IPCC, 2014). *Based on these daily projections, climate indicators were calculated for the reference past-period, the near (2020-2040) and far (2040-2060) future at the seasonal level as expected by vegetable farmers involved in the participatory project carried out after the exploratory presented in this paper* (Touili et al., 2023, 2022). *These indicators were used to characterize median and extreme conditions (one year out of five) as required by farmers. We present here only a simplified synthesis to provide a general overview of the changes to be expected.* ***These data were not presented to farmers interviewed in this study.***
**The characterization of soil humidity is based on the Standardized Soil Wetness Index (SSWI) developed in the CLIMSEC project (http://www.drias-climat.fr/accompagnement/sections/187). In the past reference period, soil wetness is “normal” for all seasons.*

A.2 Percentage of variance explained in MCA considering adaptation responses (33,2% of variance explained with dimension 1 and 2).



A.3 MCA factor map for adaptation responses and farm and farmer characteristics as supplementary variables.



Adaptation responses (1 means "presence", 0 means "absence") are presented in red (see coding in Table 4) and supplementary variables in green (see Table 1 and 2.4).

A.4. Relations between adaptation responses farm and farmer characteristics, and the first two dimensions of the multiple correspondence analysis (MCA). Student's t-tests were based on one-way ANOVA that explained the farms' coordinates on the related MCA dimension (Dim) using the categories. Only categories with p < 0.1 were kept. Categories whose estimates have the same sign are related.

Relation between dimension 1 and variables (1-way anova, F-test)

	R2	p-value
Physicalprotection	0.6767701	5.026359e-05
Trees	0.5630862	5.202472e-04
Irrigation	0.3104485	2.015086e-02
UAA_Veg	0.2029071	6.959891e-02
No_modif	0.1958482	7.526139e-02
Div	0.1773973	9.223933e-02
Equipment	0.1721203	9.774394e-02

Relation between dimension 1 and the different categories of variables (T-test)

	Estimate	p-value
Physicalprotection=Physicalprotection_0	0.3736100	5.026359e-05
Trees=Trees_0	0.3953965	5.202472e-04
Irrigation=Irrigation_1	0.2605972	2.015086e-02
Farm.creation=>=15yr	0.3658223	3.315663e-02
UAA_Veg=>=5ha	0.2045722	6.959891e-02
No_modif=No_modif_0	0.1981712	7.526139e-02
Div=Div_1	0.2219315	9.223933e-02
Equipment=Equipment_0	0.1857791	9.774394e-02
Equipment=Equipment_1	-0.1857791	9.774394e-02
Div=Div_0	-0.2219315	9.223933e-02
No_modif=No_modif_1	-0.1981712	7.526139e-02
UAA_Veg=<5ha	-0.2045722	6.959891e-02
Irrigation=Irrigation_0	-0.2605972	2.015086e-02
Trees=Trees_1	-0.3953965	5.202472e-04
Physicalprotection=Physicalprotection_1	-0.3736100	5.026359e-05

Relation between dimension 2 and variables (1-way anova, F-test)

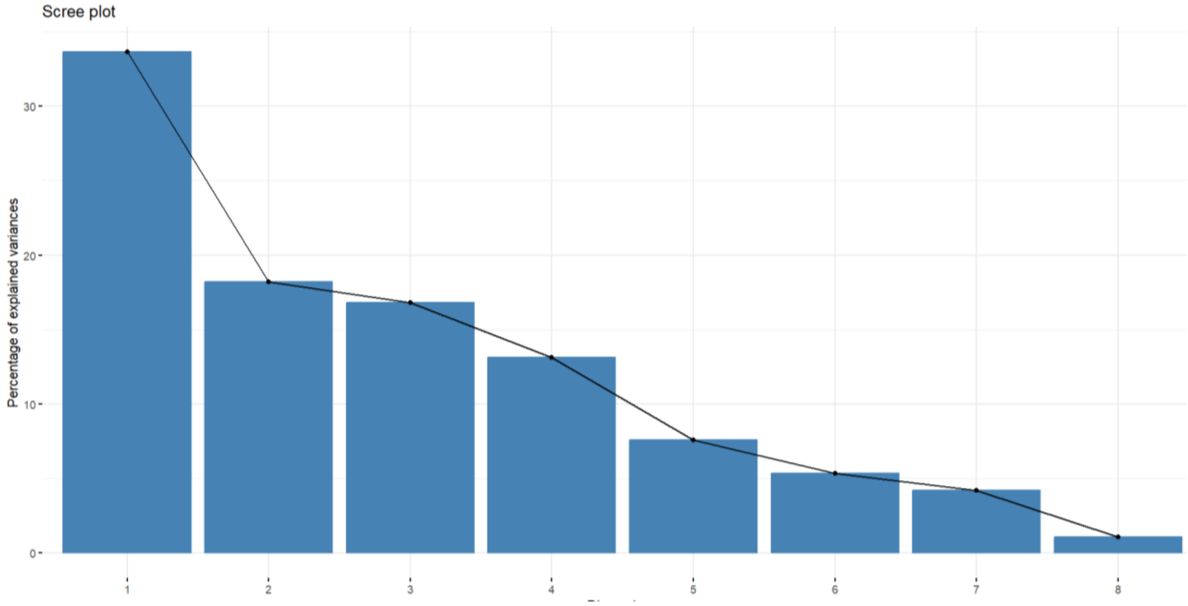
	R2	p-value
Always	0.5361399	0.0008315545
PlanningR	0.4452843	0.0034282322
Eco	0.1939682	0.0768425506

Relation between dimension 2 and the different categories of variables (T-test)

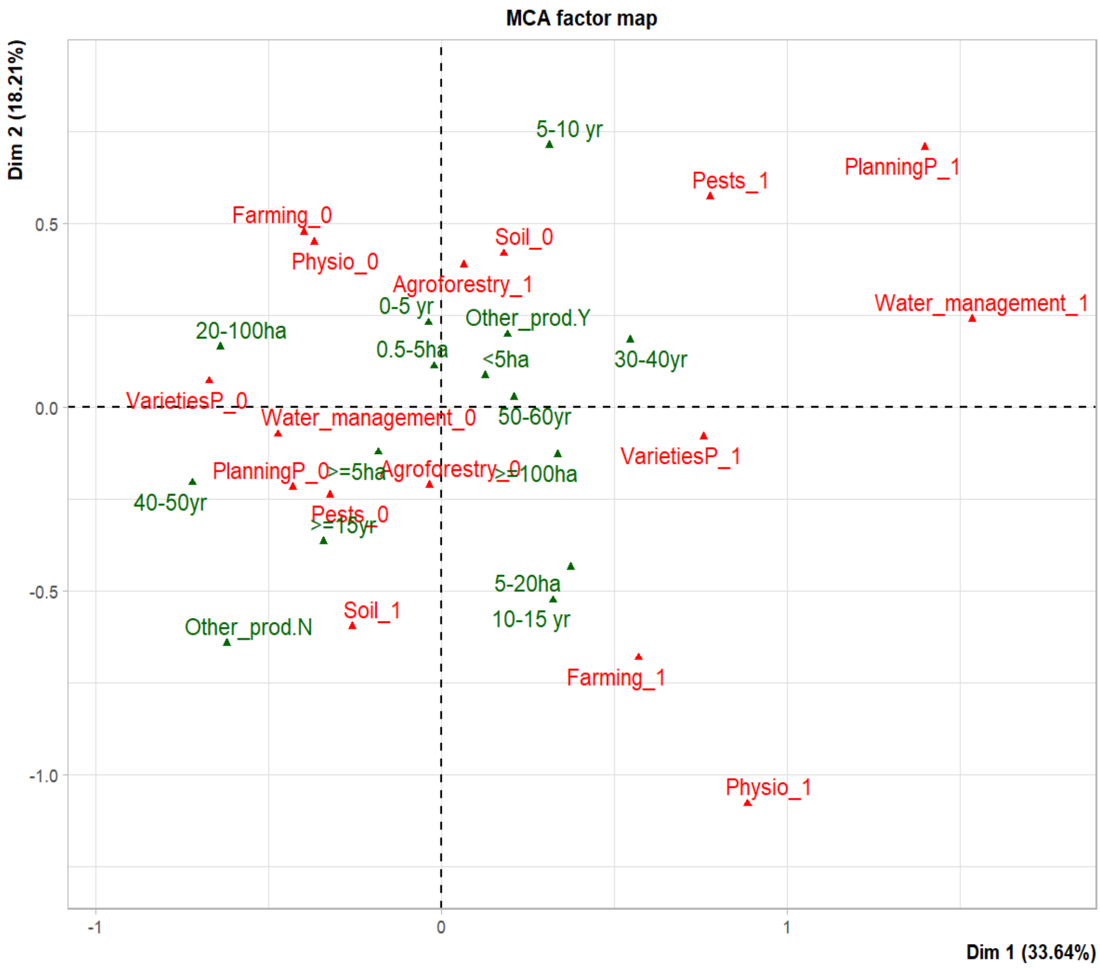
	Estimate	p-value
Always=Always_0	0.2883318	0.0008315545
PlanningR=PlanningR_0	0.2627678	0.0034282322
Eco=Eco_1	0.2040719	0.0768425506
Eco=Eco_0	-0.2040719	0.0768425506
PlanningR=PlanningR_1	-0.2627678	0.0034282322
Always=Always_1	-0.2883318	0.0008315545

See coding of adaptation responses in Table 4 (1 means "presence" and 0 means "absence") and for supplementary variables, see Table 1. Categories of supplementary variables are presented in bold.

A.5. Percentage of variance explained in MCA considering adaptation plans (51,85% of variance explained with dimension 1 and 2).



A.6. MCA factor map for adaptation plans and farm and farmer characteristics as supplementary variables



Adaptation plans (1 means "presence", 0 means "absence") are presented in red (see coding in Table 5) and supplementary variables in green (see Table 1 and 2.4).

A.7. Relations between adaptation plans, farm and farmer characteristics, and the first two dimensions of the multiple correspondence analysis (MCA). Student's t-tests were based on one-way ANOVA that

explained the farms' coordinates on the related MCA dimension (Dim) using the categories. Only categories with p < 0.1 were kept. Categories whose estimates have the same sign are related.

Relation between dimension 1 and variables (1-way anova, F-test)

	R2	p-value
Water_management	0.7254268	1.435705e-05
PlanningP	0.6015329	2.536941e-04
VarietiesP	0.5095563	1.289474e-03
Physio	0.3268831	1.649311e-02
Pests	0.2515834	4.023348e-02
Farming	0.2272302	5.303872e-02
Age	0.3007909	8.170516e-02

Relation between dimension 1 and the different categories of variables (T-test)

	Estimate	p-value
Water_management=Water_management_1	0.5822703	1.435705e-05
PlanningP=PlanningP_1	0.5302217	2.536941e-04
VarietiesP=VarietiesP_1	0.4147241	1.289474e-03
Physio=Physio_1	0.3638732	1.649311e-02
Pests=Pests_1	0.3192235	4.023348e-02
Farming=Farming_1	0.2808752	5.303872e-02
Farming=Farming_0	-0.2808752	5.303872e-02
Pests=Pests_0	-0.3192235	4.023348e-02
Age=40-50yr	-0.4243687	2.801713e-02
Physio=Physio_0	-0.3638732	1.649311e-02
VarietiesP=VarietiesP_0	-0.4147241	1.289474e-03
PlanningP=PlanningP_0	-0.5302217	2.536941e-04
Water_management=Water_management_0	-0.5822703	1.435705e-05

Relation between dimension 2 and variables (1-way anova, F-test)

	R2	p-value
Physio	0.4855682	0.001881177
Farming	0.3246754	0.016946440
Soil	0.2499210	0.041005988

Relation between dimension 2 and the different categories of variables (T-test)

	Estimate	p-value
Physio=Physio_0	0.3262773	0.001881177
Farming=Farming_0	0.2470092	0.016946440
Soil=Soil_0	0.2167154	0.041005988
Soil=Soil_1	-0.2167154	0.041005988
Farming=Farming_1	-0.2470092	0.016946440
Physio=Physio_1	-0.3262773	0.001881177

See coding of adaptation plans in Table 5 (1 means "presence" and 0 means "absence") and for supplementary variables, see Table 1. Categories of supplementary variables are presented in bold.