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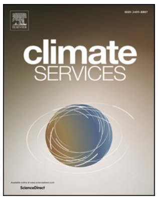

Original research article

What do vegetable farmers expect from climate services to adapt to climate change by 2060? A case study from the Parisian region

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ABSTRACT

Climate services are an important tool providing information for many sectors to adapt to climate change. For agriculture, the impacts of climate change vary between regions and between crops, and farmers' needs for climate information are also determined by local context. The purpose of this paper is to identify the climate information needs of vegetable farmers, and to discuss these needs within the specific context of the Parisian region. Based on participatory workshops in three areas of the Parisian region, and using regional downscaled data from the French climate services, this study addresses the following question: what do vegetable farmers of a *peri*-urban area expect from climate services to adapt to climate change by 2060? Participatory workshops with agricultural expert allowed us to build a preliminary set of climate variables based on crops' vulnerability to high temperatures, mild temperature in winter, late frost, low relative air humidity, low precipitation, and climate extremes such as drought, heat waves and floods. Based on this set of variables climate projection on monthly, seasonal, and annual scales were provided to farmers for the near (2021–2040) and distant (2041–2060) future, as well as for past period (1990–2020) and discussed during 3 participatory workshops. Based on farmer's feedbacks, we made a synthesis of climate information required by farmers which was validated and further discussed in a last round of workshops involving farmers and agricultural advisers. Three main findings emerge from this participatory study. Our first finding shows the need for both climate and non-climate information for vegetable farming adaptation. Specific needs include information on wind speed peaks and directions, soil moisture, climate analogous spaces (or sites), and urban planning regulations (constraining the possibility to build greenhouses or tunnels to adapt to climate change). Our second finding is that farmers expect from climate services to visualise a comprehensive climatic situation, that is, a whole conjunction of several inter-related variables, rather than precise and detailed variations of a single one. Seasonal and annual time scales seem to be the most relevant for farmers' adaptation strategies (except for frost requiring more precise information). Our third finding is that these needs remain context-specific and depend on water access, the market demand (here Parisian), and the *peri*-urban location.

Practical implications

This study identifies climate-related information needed by vegetable farmers to adapt by 2060 to climate variability and change at the scale of the Parisian region. It is a participatory approach which involved agronomists, climatologists and farmers. It uses regional projections of climate change, made available by the French climate services DRIAS (a French acronyme for « Donner accès aux scenarios climatiques Régionalisés français pour l'Impact et l'Adaptation de nos Sociétés et environnements »; https://www.drias-climat.fr). We have focused our analysis on three sites in the Parisian region. Our findings meet the growing need to anticipate climate-related risks for local vegetable production, especially in the current context of agro-ecological transition and food resilience.

A stepwise process progressively sharpened the content (and form) of our results showing that farmers need to grasp holistically a "climatic situation" complemented with non-climate

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information. In this regard, they need:

- Information regarding thermal stress due to high temperatures: projection of spring and maximal temperatures (number of days with maximal temperatures (Tmax) > 30 °C; daily thermal amplitudes (Tmax-Tmin)).
- Projection of autumn and winter mean temperatures and thermal amplitudes are needed to assess the impact of mild winters.
- Information regarding frost: Number of frost days (T < 0 °C) from March to April; spring minimum temperature per fortnight; the dates of the last spring frost and of the first autumn frost.
- Seasonal and annual projection for low rainfall and drought: Cumulative annual Precipitation (P); maximum number of consecutive dry days (P $= 0$ mm); maximum of precipitation sum over 3 days > 30 mm; number of days with P (Precipitation)-PET (potential evapotranspiration) < 0 during spring and summer.
- Projection of spring and summer heatwaves (number of days with minimal T > 18 °C and maximal T > 32 °C for at least 4 consecutive days; maximum frequency and duration of heat waves).
- The frequency, and directions, of winds above 65 km/h expected per year.
- Soil moisture by season indicated by Standardised Soil Wetness Index (SSWI) at the French climate services.
- Climate analogous spaces for future spring and summer.
- Changes in urban planning regulations impacting the location and characteristics of greenhouses and tunnels allowing to adapt to climate change.

This stepwise process also led to a shift from the (initial) time horizon of 2060 for the climate projection to a near (2021–2040) and distant (2041–2060) future. While a 30-year period is generally the rule for assessing climate variability, the two time horizons, 2021–2040 and 2041–2060, capture in our sample both the interest of young farmers, who are looking ahead 40 years, and that of older farmers, who are looking ahead to the near or very near future“. Even for a same territory and agricultural sector, socio-economic conditions (age and sources of income) of farmers, sub-categories (organic and conventional farming), as well as local administrative constraints may influence the results of the participatory process.

Comparative studies could enrich our results. The French climate service DRIAS offers a large number of Regional Climate Models (RCM) simulations based on different forcing scenarios for the future (RCP 2.6, RCP 4.5 and RCP 8.5). As we have only used one RCM/GCM (Global Circulation Model) and the RCP4.5 forcing scenario, our method would be interesting to replicate, in order to assess whether the choice of this model and climate scenario has an impact on the needs of the stakeholders.

Users' (tailored) needs in terms of climate, and non-climate, information suggest new avenues for the field of climate services:

- Some of the climate-relevant variables identified are not currently available on the French climate services, such as annual frequency, and directions of wind speed peaks over 65 km/h, probably because the uncertainty is too high to provide reliable information about the future, or such as climate analogous spaces, probably because national climate services have to extend their scope at an international scale to meet this need.
- The output format of climate services is of major importance for famers who expect to a “climatic situation” as an output product bringing together a range of relevant climate information. In order to provide an overall vision and a sort of reality of climate conditions for vegetable farming, high temperatures, for example, are requested in conjunction with soil moisture, low rainfall and drought, climate analogous spaces and thermal amplitudes. Another example is the wind speed peaks and directions that farmers require in conjunction with the risk of late frost.

The study points out the importance of understanding farmers' needs. For climate services, identifying user needs is important for the present, while understanding why these specific needs exist is fundamental for the future. The specificity of the vegetable sector in general, and in the *peri*-urban context of the Parisian region in particular, largely determines our results. In this regard, the needs that emerge from our study remain strongly determined by three drivers: farmers' access to water, the Parisian demand market and the farms' *peri*-urban location.

This study has also had practical implications for research projects. Using DRIAS climate service as a starting point, within the ClimaLeg project (adaptation of vegetable farming to climate change by 2060), our results have prompted an extension towards the availability of water resources, as a marker of climate change for vegetable farmers, for the ClimaLeg-Eau project (https://www6.versailles-grignon.inrae.fr/sadapt/Focus/ClimaLeg-Eau). Expanding research in the field of “water” comes at the same time as a new component called DRIAS-Eau (https://www.drias-eau.fr/), to make available future hydro-climatic projections under climate change.

Within the ongoing context of agro-ecological transition and food resilience, climate services are likely to guide public policies through climate information on the prospects for relocalising agriculture and food production at local scales. What food can be (locally) produced and where in the future?

Introduction

Climate change is a major issue for many sectors, and particularly for agriculture. Of all human activities, agriculture is the most dependent on weather conditions (Hansen, 2002). With an estimated world population of 10 billion by 2060,[1] the impacts of climate change on global food production will represent a major challenge to humanity. Agricultural activities are heavily affected by short- and long-term variations in several climatic factors such as temperature, precipitation, humidity and winds, as well as by extreme weather events such as drought, floods, heat waves and frost (IPCC, 2012). As climate change impacts can vary by region and by crop, more local and relevant climate information becomes essential for farmers' adaptation. In this respect, climate services are a growing concept to support farmers' adaptation needs.

Climate services could be defined as “scientifically based information and products that enhance users' knowledge and understanding about the impacts of climate on their decisions and actions”.[2] The objective of climate services, also called climate information services (Tall et al., 2018; Carr et al., 2020), is to enable individuals and organisations to take appropriate adaptive and preventive measures (Lémond et al., 2011). Goosen et al. (2014) used the term “climate adaptation services” as climate information helps users significantly to determine their future adaptation strategies. Climate services provide information on climate and should not be confused with meteorological services, which describe short-term atmospheric conditions at a given place.[3] Climate services provide information of averaged weather conditions, using analysis of time series data to estimate trends, deviations from average conditions, and low-probability events over a range of time scales (Dutton, 2002; World Meteorological Organization, 2011). Efforts to develop climate

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[1] FAO (Food and Agriculture Organization). (2009). Global agriculture towards 2050. In *Proceedings of the High Level Expert Forum—How to Feed the World* (Vol. 2050, pp. 1–4).

[2] The American Meteorological Society (AMS).

[3] National Research Council. *A climate services vision: First steps toward the future*. National Academies Press, 2001.

services have increased rapidly since the 1997/98 El Niño phenomenon, to meet the growing demand (Goddard et al., 2010; Tall et al., 2018). Climate services cover a wide range of users as new technologies – satellites, radar, telecommunications, and supercomputers – enable increasingly accurate forecasts of climate events and more refined and extensive long-term climate projections (Vaughan and Dessai, 2014). To meet growing and varying needs, climate services contribute to "transformation of climate-related data – together with other relevant information – into customised products such as projections, forecasts, information, trends, economic analysis, assessments (including technology assessment), counselling on best practices, development and evaluation of solutions and any other service in relation to climate that may be of use for society at large" (European Commission, 2015).

It is worth noting that the growing interest in climate services also results from societies' awareness of the impact of climate and the pressing need to mitigate vulnerabilities and plan adaptation. Whilst the importance of climate services is recognised, matching the supply of climate information to user needs is an ongoing challenge. Many studies have already been carried out on specific climate information for a variety of fields (Soares and Dessai, 2015), to support long-term renewable energy such as wind, solar, and hydropower (Howland et al., 2019; Bartok et al., 2019; Halsnæs et al., 2021), specifically with regard to transport (Umar et al., 2021), tourism (Scott et al., 2011; Damm et al., 2020), water resources management (Cremades et al., 2021; Tudose et al., 2022), and public health (Lowe et al., 2017; Stewart-Ibarra et al., 2019). For agriculture, most climate information has been provided at a national scale from the national meteorological services (Hansen et al., 2019), and many efforts have recently been dedicated to developing agro-climate tools and applications such as ClisAgri (agro-climate service tool) (Ceglar et al., 2020) and GETARI (Generic Evaluation Tool of AgRoclimatic Indicators) (De Cortazar Atauri and Maury, 2019).

This paper is in line with previous studies that highlighted the importance of providing climate-relevant information to a specific subsector in a given context (Buontempo et al., 2014). In this respect, vegetable production is especially challenging.

Like other agricultural crops, vegetables are impacted by changes in climatic patterns and extreme events which lead to crop failures, lower yields and quality, and increased pressure from pests and diseases (Morel and Cartau, 2023; Ayyogari et al., 2014). Erratic rainfall patterns and extremely high temperatures have far-reaching impacts on horticulture in general and vegetable crops in particular (Fadairo et al., 2020; William et al., 2018; Datta, 2013). Most vegetables have high water requirements and limited soil moisture is a major cause of yield losses (Williams et al., 2019) as it strongly affects several physiological and biochemical processes (Ayyogari et al., 2014). Even moderate elevations of day and/or night mean temperatures can affect the yield and quality of some crops like spinach, potato, broccoli, and lettuce. Vegetables include a wide variety of botanic families, crop types (e.g. root, leaf fruit vegetables), length of growing cycles and harvesting periods. They can be grown outdoors or in shelters, and many vegetable farmers combine outdoors and sheltered production. As vegetables often have shorter cycles than cereal crops, farmers can grow various cycles on the same plot over the year. Vegetable farms can be highly diversified, producing a wide range of crops over the year to match the requirements of their marketing channels, especially if they are involved in short supply chains such as open-air markets or CSA (Community Supported Agriculture) vegetable box schemes (Navarrete, 2009; Morel et al., 2018). Vegetables are highly perishable products for relatively short-term consumption or processing. Moreover, most small-scale vegetable producers have limited storage facilities. This makes vegetable farmers particularly vulnerable to climate conditions. On the other hand, growing a wide diversity of short cycle vegetable crops over the year provides levels of freedom to react and adapt to climate constraints (Morel and Cartau, 2022). All these characteristics highlight the need for climate-relevant information for vegetable farmers.

The purpose of this paper is to address the following question: what do vegetable farmers expect from climate services to adapt to climate change by 2060? Adaptation refers here to "the process of adjustment to actual or expected climate and its effects in order to moderate harm or take advantage of beneficial opportunities" (IPCC, 2014); and vegetable farmers' adaptation in particular is linked to the need for information to explore strategic decisions (e.g. crop choice, technical systems, marketing channels, investments) rather than operational, day-to-day or tactical decisions.

We followed a step-wise process based on workshops with local agricultural experts and farmers, involving discussions on downscaled climate projections derived from the French climate services DRIAS (https://www.drias-climat.fr/accompagnement/sections/296). This paper does not deal with the performance of climate modelling, as the biases and uncertainties of regional climate simulations and projections are acknowledged and discussed in many studies (Aalbers et al., 2018; Coppola et al., 2020; Vautard et al., 2021; Bartok et al.,2021), including decision making issues (Baldissera Pacchetti et al., 2021). Participatory processes have often taken the form of working groups that co-produce relevant variables, not only with climate service experts (Peterson et al., 2001; Tall et al., 2014) but also with local communities, with regard to the scaling up of climate services for farmers (Tall et al., 2014). Using climate data, participatory processes are also involved in assessing vulnerability (Mattos et al., 2014; Jonsson et al., 2012; Touili et al., 2022) and/or co-designing farming and livestock systems adapted to climate change (Sautier et al., 2017). For vegetable farming, studies using regional model-based climate projections remain very scarce, especially in Europe. While some research has focused on vegetables farmers' perceptions of climate variability and adaptation trends (Fadairo et al., 2020; Williams et al., 2019), most recent research has been dedicated to assessing climate services for farmers in African and/or Asian contexts in general (Carr et al., 2020; Gwenzi et al., 2020; Vincent et al., 2020; Nkiaka et al., 2019).

Using bias-corrected and downscaled climate data, our results on climate-relevant variables and appropriate time scales are expected to support both users and providers of climate information – respectively vegetable farmers and regional climate services – to meet context-specific adaptation needs.

This paper is structured in three major sections. The next section, "Context, research design and data collection process", describes the context-specific case of vegetable farming in the Parisian region, as well as our participatory approach. Using downscaled climate projections derived from the French climate services, our study was based on six participatory workshops with local agricultural experts and vegetable farmers, in three areas. This approach allowed us to iteratively refine farmers' requirements for climate information. The "results and discussion" section outlines our findings stepwise, showing how we obtained a final set of climate information requested by vegetable farmers to adapt by 2060. Our findings are analysed and discussed within the specific context of the Parisian region. The paper concludes with overall reflection on the participatory process itself, in light of the study's findings, and proposes directions for future research.

Context, research design and data collection process

The context-specific case of vegetable farming in the Parisian region

In the Parisian region, vegetable farming is undergoing rapid expansion – in terms of production areas – and a rise in public and political interest within a trend towards agro-ecological transitions and food resilience. Within the framework of the National Food Programme, the French government is taking action to develop safe, local and sustainable food through territorial food projects (PAT[4]). These projects aim to relocalise agriculture and food production in territories by

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[4] Projets Alimentaires Territoriaux (PAT).

supporting the installation of farmers, promoting short circuits and meeting the growing public demand for more local products.

The Parisian region is the largest urbanised region in France, but is also a major agricultural region with 562,220 ha of Utilised Agricultural Area (UAA). Vegetable crops account for only 4,500 ha (DRIAAF[5] Ile-de-France, 2019) of the total UAA, which is covered primarily by arable crops. The vegetable sector has however recently undergone significant changes. There has been a shift in the number of vegetable farms and in sales methods. In 2020, the number of vegetable farms almost doubled compared to 2010 (Agreste, 2021). A trend towards diversification from arable crops to vegetables is taking place, as well as the setting up of new farms specialised in market gardening, mostly by new entrants. Most of them are choosing organic market gardening as a meaningful profession, and farm small areas to reduce initial investments and overcome the difficulty of access to land (Morel and Léger 2016). These new entrants coexist with longstanding vegetable farms that generally occupy larger acreage with a higher level of mechanisation. Although local agriculture is not a relatively recent phenomenon, it has recently been accompanied by a trend towards the consumption of local food. A growing regional demand for local products can be seen in different supply chains (e.g. collective catering, CSA box schemes, supermarkets), especially fresh vegetables that play an important role in diets. The Parisian region consumes 895,500 tonnes of fresh fruit and vegetables per year, almost ten times more than it produces (98,000 tonnes) (Interfel, 2019).[6] In last decade, nearly 70 % of vegetable farms were involved in short circuits and two thirds of them made more than 75 % of their turnover from vegetables and/or fruit (Cheveau et al., 2014). The vegetable sector has recently benefited from regional policies and programmes such as the territorial food projects (PAT) or the Paris sustainable food plan[7] to support the growth of short supply chains within the Parisian food system. With regard to food security and sustainability, local agriculture (whether organic or conventional) connects farmers to the 12.3 million inhabitants, in a territorialised agri-food system in the Paris region.

Mainly located in the Paris *peri*-urban areas, vegetable farming remains under the pressure of expansionist urbanisation (Mawois et al., 2011; Aubry and Kebir, 2013) and competition from national and/or international products. The Greater Paris Metropolis– created on 1 January 2016 as an extension of the city of Paris by an inter-municipality grouping 131 cities – already includes 102 farms, i.e. around 2,000 ha of agricultural land.[8] Large metropolitan urban projects are likely to reduce agricultural areas. However, one of the major concerns arises from the impact of climate change on vegetable crops. They have recently been adversely affected by changes in certain climate factors and/or the frequency, duration and extent of extreme events, leading to crop failure, poor yields, reduced quality and an increase in crop pests and diseases (Morel and Cartau, 2022). Such concerns about the local impact of climate change have been reported by farmers' networks and key regional agricultural extension and support services such as the GAB (regional organic farmers' interest grouping)[9] and the Chamber of Agriculture.

Few studies have been carried out on the climate change impacts on vegetables in the Parisian region (Morel and Cartau, 2022). Information about climate change is available for France at the daily time scale and with spatially gridded data at 8 km scale resolution, via the French climate services portal DRIAS (https://www.drias-climat.fr/accompagnement/sections/181). To anticipate adaptation to climate change, farmers have expressed interest in translating those existing climate data into relevant indicators for the vegetable sector and on shorter time horizons than the end of the 21st century. In this context, a participatory project called ClimaLeg (adaptation of vegetable farming to climate change by 2060 in the Parisian region), to which this study belongs, was launched in 2021 with researchers and experts from local agricultural extension services.

Participatory workshops

This research was carried out in three major steps relying on a total of 6 workshop sessions with local agricultural experts and farmers, organised from October 2021 to March 2022 (Fig. 1).

First step: two workshops with agricultural experts to build a preliminary set of climate-relevant variables to use on climate projection

As a starting point, two workshops were held in October 2021 with 10 experts from the main regional agricultural extension and support services, namely the Chamber of Agriculture, the GAB, "Terre et Cité" (a local association promoting agriculture on the "Plateau de Saclay" area in the south-west of the Parisian region) and INRAE (The French National Research Institute for Agriculture, Food and Environment). Drawing on scientific literature and past experience, these workshops aimed to answer the following questions:

- Which climate variables or extreme weather events can affect vegetable crops? When? How?
- What climate variables and time-scales are relevant for vegetable farmers' adaptation?

From a wide range of climate-related risks, our first step pointed out a preliminary set of climate-relevant variables based on crops' vulnerability to high temperatures (T), mild temperature in winter, late frost, low relative air humidity (H), low precipitation (P), and extreme events of drought, heat waves and floods. With the exception of floods, these climate variables are all available (or can be derived) from the French climate services. For example, heat waves are defined as periods where daily minimal temperature is above 18 °C and maximal temperature above 32 °C for at least 4 consecutive days. This definition provided by agricultural experts is commonly used in the area and allows to estimate heat waves based on available climate variables.

In view of the subsequent workshops with local farmers, these first two workshops also made it possible to identify three areas of vegetable crop clustering within the Parisian region with differing pedoclimatic conditions: the "Plateau de Saclay" (south/south-west of the Paris region); the "Plaine de Cergy" (north-west of the Paris region); and "Le Mée-sur-Seine" (south-east of the Paris region).

The preliminary set of climate-relevant variables built with agricultural experts was used on a climate projection derived from the French climate services and using the R-statistics software (see Section 2.3). Agricultural experts assumed that providing climate projections for the 2021–2040 and the 2041–2060 period, was more likely to capture the interest of both young farmers, recently settled and looking ahead 40 years, and older farmers looking ahead 10 or 20 years.

Second step: three workshops with farmers to discuss climate projection and express their needs

This climate projection (in the form of graphs) was the basis of the second step of our approach. In December 2021, this information was presented and discussed with 23 vegetable farmers in 3 workshops, one in each of the 3 selected zones (Fig. 2, Table1).

Table 1 displays the profiles and characteristics of the cropping and production systems of vegetable farmers participating in the workshops. In our sample, vegetable surface areas ranged from a minimum of 1.2 ha to a maximum of 80 ha. We distinguish two types of vegetable systems: large scale farmers combining cereals with vegetable production involved in short supply chains, sometimes combined with long supply chains and, market gardeners (specialised vegetable farmers), all

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[5] Direction Régionale et Interdépartementale de l'Alimentation, de l'Agriculture et de la Forêt (DRIAAF).

[6] Interprofession des fruits et lègumes frais (Interfel).

[7] Plan Alimentation Durable de Paris (https://www.paris.fr/pages/un-plan-alimentation-durable-pour-paris-2705).

[8] https://www.metropolegrandparis.fr/sites/default/files/2020-02/Comptes-rendus%20Rencontres%20Agricoles%20-%20Annexe.pdf.

[9] GAB (Groupement des Agricultures Biologiques).

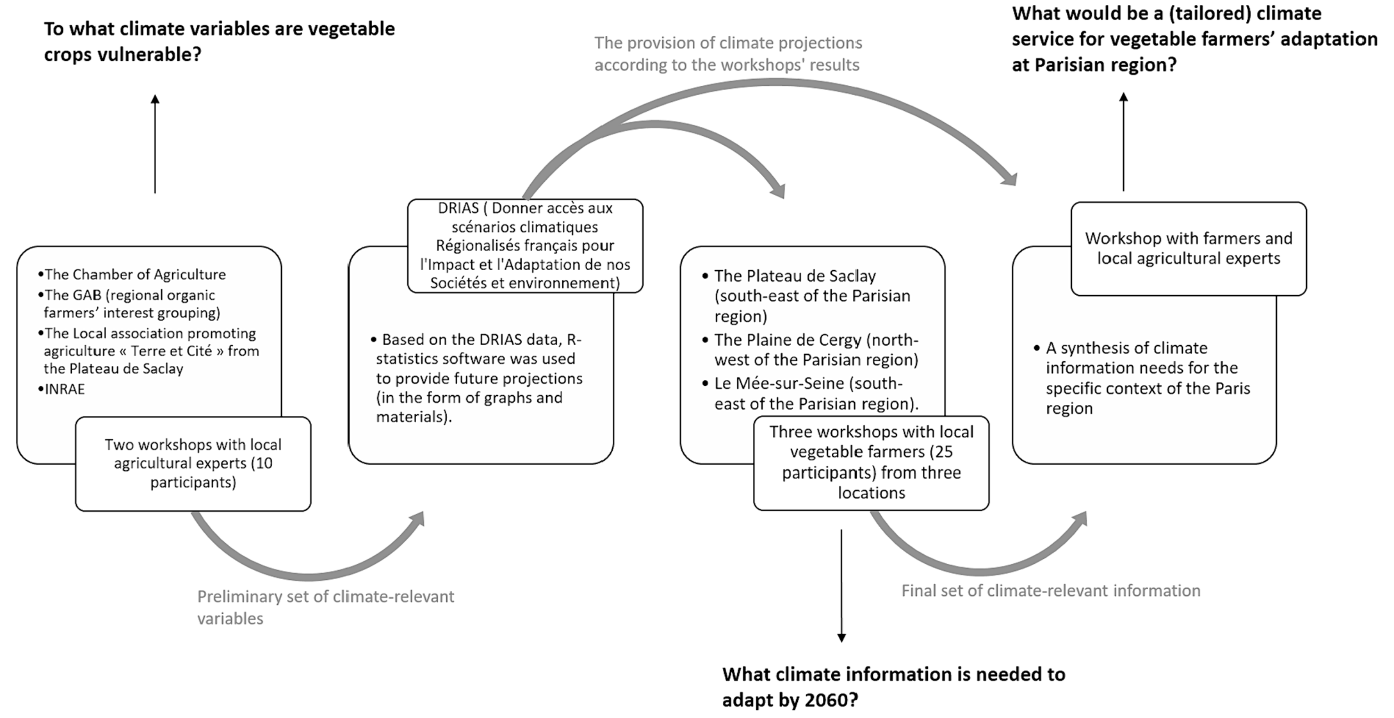

Fig. 1. Outline of the participatory approach followed.

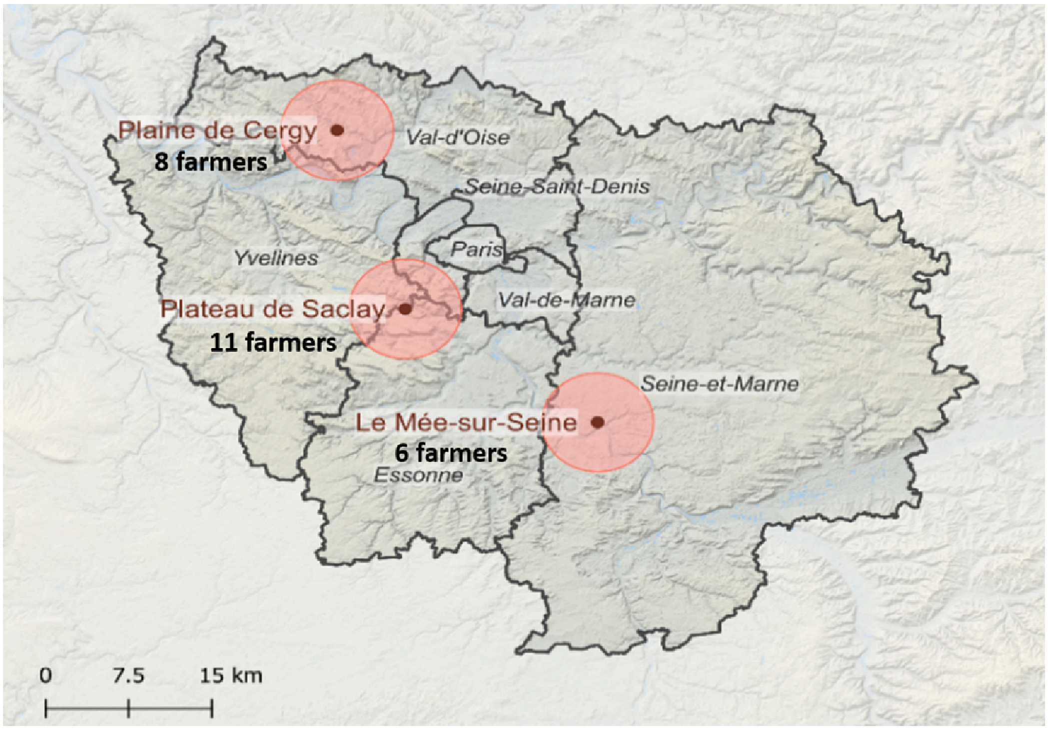

Fig. 2. Locations of the three selected sites and number of vegetable farmers involved in the workshops. Characteristics of farms are described in Table 1 below.

involved in direct sales and /or in AMAP,[10] the French version of CSA box schemes. Except for one farmer who only grows vegetables in open fields, most farmers combine outdoors production with sheltered production (in greenhouses or tunnels), with the aim of ensuring stable, early production throughout the year. As shown in Table 1, participants represented different vegetable production types, farming methods and marketing channels (Fig. 2). Our workshop groups involved both long-standing farmers, and recently-established market gardeners.

The different graphs illustrating the climate projection based on the preliminary set of climate-relevant variables (see Section 2.3) provided during the farmers' workshops were used to launch dialogue and generate discussions on the relevance of the data presented and the needs/expectations in terms of climate information. Based on the results

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[10] AMAP (Association pour le Maintien de l'Agriculture Paysanne).

Table 1
Number and characteristics of vegetable systems of the farmers participating in the workshops according to location.

		Plateau de Saclay (11)	Plaine de Cergy (8)	Le Mée-sur Seine (6)
Vegetable production types	Combining vegetables and cereals	5	3	4
	Specialised in vegetables	6	5	2
Farming methods	Organic farming	8	4	4
	Conventional farming	3	4	2
Marketing channels	Direct sales (retail on farm and/or open-air markets)	9	7	3
	100 % AMAP (French CSA box scheme)	2	1	3
	Long supply chains	3	–	2

of step 1, graphs were fully described and accompanied by a detailed explanation (see Section 2.3).

For each graph presented and discussed, participants of each workshop were asked the following question:

- What do you think about these climate variables, and the projection's time scales?

  At the end, a more general question was asked:

- In order to anticipate climate change in a near and distant future, which climate information do you need and at what time scales?

Each workshop lasted in average 4 h and was fully recorded, in agreement with the participants, and transcribed (46 pages, with 104,614 characters). This material was processed through qualitative analysis methods (Miles and Huberman, 1994) involving a review of all comments and feedback (by graphs displayed and for each workshop) and subsequent sorting into categories (feedback on the climate variables presented, additional information requested and the purpose it was to serve, relevant time scales, other needs expressed). This process eventually resulted in a synthesis of climate information requirements and insights to explain and understand them. Based on the analysis of farmer's feedbacks, we generated a new synthetic table showing the climate projection with climate variables judged relevant by farmers. Providing a synthetic table gathering all climate variables rather than many separate graphs was a key point raised by farmers as it allows a more systemic view of climate change (see results).

Third step: a final workshop to validate and further discuss climate information needed by vegetable farmers

In March 2022, this new synthetic climate table with a final set of climate information was presented to vegetable farmers and local agricultural experts from across the Parisian region in a last collective workshop.

The objective of this step was to validate the synthesis made from the feedbacks of step 2 and to discuss famers' needs from climate services. The workshop took place both in person and by video conference, due to the limited availability of vegetable farmers at this time of the year. This step resulted in a final set of climate-relevant information that farmers require to be able to adapt by 2060 to the context of the Parisian region.

Using climate data from the French climate services DRIAS

In France, the DRIAS climate service portal was launched in 2012, as a response from the French scientific community to society's need for climate information (Dandin et al., 2012; Lémond et al., 2011). Thanks to EURO-CORDEX (Coordinated Regional Climate Downscaling Experiment-European Domain community), this portal provides regional and relatively small-scale (64 km^2) projection of many climate variables (https://www.drias-climat.fr/accompagnement/sections/40). The ultimate goal of this French climate services is twofold: to promote the use of climate data by identifying societal needs; and to support mitigation and adaptation decision-making by providing easy access to French regional climate data and products. In line with users' needs for climate data, there is a considerable progress in high resolution regional climate model (RCM)-based projections. Long-term projections are now available for a wide range of climatic factors within slices of short- and long-term (end of century) horizons[11] at daily, monthly and seasonal time scales.

Within our participatory approach, we used the downscaled and bias-adjusted CLMcom-CCLM4-8-17/MOHC-HadGEM2-ES (GCM/RCM) simulations model and the RCP 4.5 emission scenario, which is neither optimistic (i.e., RCP2.6, close to the Paris Agreement) nor pessimistic (i.e., 8.5). From 1950 to 2099, a large set of daily climatic data is provided: minimum, maximum and mean temperatures (T) at 2 m above ground level, total rainfall (P) and large-scale snowfall, specific humidity (H), wind speed at 10 m above ground level and potential evapotranspiration (PET).

It is worth noting that there is a wide range of regional models available in DRIAS (https://www.drias-climat.fr/accompagnement/sections/240). In our case, the use of one climate projection and the performance of the selected simulation model (GCM / RCM) are not considered decisive with regard to the purpose of this paper. As far as we are concerned, climate projection is merely deployed here as a very concrete discussion tool with the objective of finding out the needs of farmers to anticipate climate change in the Paris region. In each workshop, we informed participants about the DRIAS portal used as a source for our climate data, and highlighted the uncertainties associated with climate data in general.

Agricultural studies of climate impacts need downscaling in climate data. We thus used an 8 km*8 km continuous grid that corresponds to the French climate data grid system, SAFRAN (Vidal et al., 2010). The finest resolution of data available on the DRIAS is considered sufficient by farmers, and is the one we have used for the three selected sites (i.e. the "Plateau de Saclay", the "Plaine de Cergy" and "Le Mée-sur-Seine"). For each site we have chosen the pixel enclosing it. Going beyond and having more site-specific climate data would imply a further downscaling of this dataset, either dynamically or statistically. The daily data available for the climate variables (e.g. temperature, precipitation, potential evapotranspiration, etc.) underwent simple statistical computations (means, medians, etc.) using the R-statistics software (version 4.2.1), to provide climate projection in the form of intelligible graphs on different time scales. Fig. 3 shows only an illustrative sample of the data projected for the "Plateau de Saclay", from the results of step 1 and using the selected GCM/RCM simulations model and scenario. Both historical and future climatic information come from the GCM/RCM models. As the regional climate information has been bias-corrected, it is close enough to observations over our three sites.

Results and discussion

This section outlines the stepwise results of our participatory workshops. First, a preliminary set of climate-relevant variables resulted from our workshops with agricultural experts. Then, a final set of climate-relevant information resulted from our workshops with farmers. The resulting tailored climate service is discussed here in light of the context-specific adaptation needs at the Parisian scale.

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[11] Horizon of 2099 or 2100 depending of the model selection.

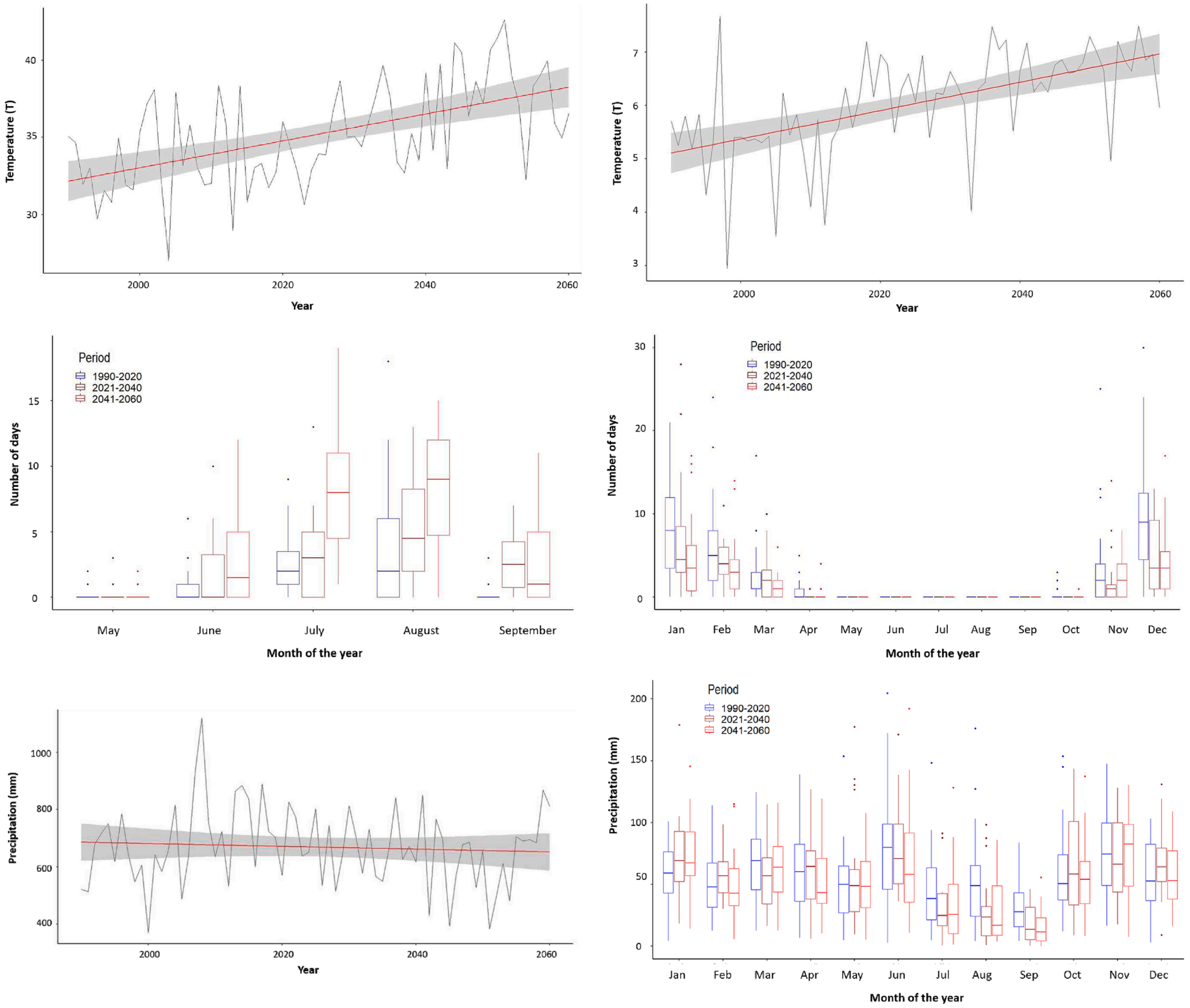

Fig. 3. Sample of climate projection graphs, derived from DRIAS data and based on the results of step 1, that were presented during the farmers' workshops. The climate projection here relates to the"Plateau de Saclay" area and was obtained using the CLMcom-CCLM4-8–17 model. On graphs 3a, b and e, the red line and grey envelope are calculated by a standard smoothing function geom_smooth (formula = y ~ x, method = lm) of the ggplot R package and only intend to ease interpretation by providing a simple increase pattern.

Preliminary set of climate-relevant variables

Table 2 provides a summary of the preliminary set of climate-relevant variables identified by agricultural experts in the workshops of step 1. Agricultural experts listed different types of vegetables according to the climate variable they were sensitive too. The main climate variables to which vegetables are vulnerable are the following: temperatures (T) above 30 °C, mild temperature in winter, late frost, low relative air humidity (H) and low precipitation (P). Drought, heat waves and floods were identified as the extreme events to which vegetables are also exposed. The climate-relevant variables and times scales were developed on the basis of effects and/or thresholds.

For instance, temperatures higher than 30 °C affect all summer sheltered crops (e.g. tomatoes, cucumbers, aubergines) and all spring outdoor crops sown in May-June (e.g. carrots, beetroot, fennel, onions). The climate-relevant variables suggested by agricultural experts were: the number of days per year with T > 30 °C, the maximum monthly temperatures from June to September, the number of days per month from May to September with T > 30 °C. In mild winters, farmers often sow crops earlier than usual in shelters to benefit from higher prices. However, our results show that these crops are likely to be frozen during the early flowering period. Frost is still a major threat to field crop vegetables. While a prolonged period of above-normal temperatures offers an advantage in terms of early yields (Craufurd and Wheeler, 2009), one or more days of frost may severely damage all crops of gelatinous vegetables (e.g. tomatoes, potatoes, aubergines, peppers, beans), especially at the seedling stage (5, 7 leaves). Another climate variable identified was air humidity for all crops (outdoors or sheltered) during winter. Air humidity has a crucial impact on pests, disease incidence, and flowering of vegetable seeds (Gopalakrishnan, 2007). With regard to warmer winters, all open field and greenhouse crops might be sensitive to a lower relative air humidity than 60 % in winter. In addition, vegetables have high water needs and generally consist of greater than 90 % water (AVRDC, 2006; La Pena, and Hughes, 2007). Therefore, they are very sensitive to low air humidity, which increases the need for evapotranspiration, and to low precipitation, and are strongly impacted by drought.

With regard to extreme events, drought is specifically harmful to

Table 2
Preliminary set of climate-relevant variables that were provided during the farmers' workshops in the form of climate projection for the near (2021–2040) and the distant future (2041–2060) with respect to the past period (1990–2020).

Main climate variables	Main effects on sensitive crops	Preliminary set of climate-relevant variables
High temperatures (T)	- *Summer sheltered crops* (*e.g. tomatoes, cucumbers, aubergines*)*:* suffering leaf and fruit scorch effects as early as one day at outdoor T > 30 °C (close to 45 °C under shelter) which leads to a loss of part of the production after 5 or 6 successive days. - *Spring field crops that are prone to bolting* (*e.g. chard, fennel, celery*): go to seed prematurely. - *Most field (small seed) crops sown in May-June* (*e.g. carrots, beetroot, fennel, onions*): experience losses at emergence stage in case of excessive T in June, mainly in case of lack of watering (irrigation).	- Number of days per year with T > 30 °C - Maximum monthly temperature from June to September - Cumulative days per month of May, June, July, August and September with T > 30 °C
Mild temperature in winter	- *All spring crops sown earlier to meet market demand* (e.g. strawberries): experience yield losses caused by frost if they flower too early.	- Mean monthly temperatures (T) from November to March
Late frost	- *Frost sensitive vegetables, especially at the seedling stage (5, 7 leaves) during spring (typical of early sowing to meet market demand):* are largely damaged by late frost.	- Minimum T values from March to end of May - Number of frost days (T < 0 °C) from November to April - Number of frost days (T < 0 °C) per year
Low relative air humidity (H)	- *All crops (outdoors or sheltered), except watermelon and melon*: are impacted by relative humidity (H) < 60 % leading to stunted plant growth, especially at high temperatures.	- Number of consecutive days with H (relative air humidity) < 60 % during winter
Low precipitation (P)	- *All crops* suffer from lack of water.	- Cumulative annual precipitation - Monthly precipitation volumes
Drought	- *Leafy* (*e.g. spinach, herbs, onions, lettuce*) *and fruit vegetables (shallow-rooted vegetables):* are strongly impacted by drought, especially after 5–6 weeks of drought during spring.	- Number of consecutive dry days (P = 0 mm) per year - Number of days with P-PET < 0 (for at least 4 weeks) from March to September
Heat wave	- *Spring and summer seedlings* (*e.g., carrots, beetroot, fennel*) *and all small seeds*: cannot resist heatwaves.	- Number of days with minimal T > 18 °C and maximal T > 32 °C for at least 4 consecutive days
Flood	- *All vegetables growing in spring* are destroyed by overflowing water.	- Number of successive days with P > threshold to be defined during farmers' workshops in each of the three selected sites) in spring months ("proxy", as only hydrological models combined with hydraulic models can provide information on flood)

leafy and shallow-rooted fruit vegetables. Sowing or planting dates depend on rainfall for most vegetables in rainfed areas, and major cropping seasons and field work are also finalised based on time and duration of rainfall (Gopalakrishnan, 2007). The climate-relevant variables retained are: cumulative annual precipitation, monthly precipitation volumes, number of consecutive dry days (P = 0 mm) per year, and number of days with P-PET < 0 (for at least 4 weeks) from March to September. Vegetable crops are vulnerable to heat waves affecting winter seedlings and all small seeds, and to particularly severe floods in spring (Table 2). The climate-relevant variable suggested by agricultural experts was the number of days with successive minimal T > 18 °C and maximal T > 32 °C for at least 4 days, in the case of heatwaves. That of flooding was excluded as it required hydrological modelling beyond the scope of our study. The Parisian region is exposed to rainfall-related floods but also to more complex water cycles at the level of the catchment areas and the Seine river.

Final set of climate-relevant information

The 3 workshops with farmers showed that climate-relevant variables suggested by agricultural experts were appropriate. However, farmers outlined specific and additional needs (Table 3).

Relevant time scales for farmers

Farmers confirmed that it was relevant to consider a near (2021–2040) and a distant (2041–2060) future. With regard to past period, farmers find it more relevant to select significant and experienced events and years as a reference for future events and years. For example, comparing future heatwaves with the reference heatwave of 2003, comparing future dry years with the reference years of 2019 and 2020, and wet years with the reference years of 2012, 2016 or 2018.

Generally, farmers were willing to access climate information summarized by season because it was easier for them to connect it with farming practices throughout the year, except for precipitation for which the annual value was also judged of interest and for frost for which more precise data were required (see below).

Farmers want to visualize a "climatic situation"

In light of climate variables, farmers seek to anticipate adverse weather conditions as well as benefit from potential opportunities arising from climate change. Unlike the preliminary set based on the vulnerability of specific crops, farmers mostly seek to visualise a climatic situation, i.e., a whole conjunction of several inter-related variables, rather than more precise and detailed variations of a single one. From the adaptation perspective, the impact of climate change is not limited to a single climate factor, as farmers often consider a wide range of short-cycle crops (from thirty to forty crops in the case of market gardeners) to plant or to sow at different periods of the year, sometimes both under shelters and in the open field (e.g. lettuce, carrots, squash). As there is no single main crop, a holistic view becomes necessary to guide the choice of crops and of possible crop rotations, in addition to succession crop planning, which involves a combination of seasonal, annual and beyond-year time scales.

Deepening of preliminary climate-relevant variables

Compared to our first results, farmers require, in addition, projection of seasonal (spring and summer) maximal daily temperatures number of days with Tmax > 30 °C and thermal amplitudes (Tmax-Tmin). Thermal amplitudes allow farmers to complete the maximum and minimum temperature information, in order to ascertain the physiological rest of the plants, especially in greenhouses/tunnels during heat periods and close to urban areas where the daytime temperatures do not decrease much at night. Similarly, projection of seasonal (autumn and winter) mean temperatures and thermal amplitudes are needed to assess mild winters. According to farmers, the frost variable requires more detailed and refined data. Farmers need fortnightly and monthly information, since their main concern is the last frost in April. Farmer's request is mainly focused on the dates of the last spring frost and of the first autumn frost, in addition to the number of frost days from April to March, and in spring (minimum temperature per fortnight).

Table 3
The final set of climate-relevant information that vegetable farmers need to adapt.

<table>
<tr><th colspan="2" rowspan="2">Climate-relevant information*</th><th colspan="4">Season considered</th></tr>
<tr><th>Spring</th><th>Summer</th><th>Autumn</th><th>Winter</th></tr>
<tr><td rowspan="3">High temperatures</td><td>Maximum daily temperature reached per season: problematic if above 30 °C</td><td>x</td><td>x</td><td></td><td></td></tr>
<tr><td>Number of days with Tmax > 30 °C</td><td>x</td><td>x</td><td></td><td></td></tr>
<tr><td>Maximal, minimal and mean daily thermal amplitudes (Tmax-Tmin)</td><td>x</td><td>x</td><td></td><td></td></tr>
<tr><td rowspan="2">Mild temperatures in winter</td><td>Mean seasonal temperature</td><td></td><td></td><td>x</td><td>x</td></tr>
<tr><td>Maximal, minimal and mean daily thermal amplitudes (Tmax-Tmin)</td><td></td><td></td><td>x</td><td>x</td></tr>
<tr><td rowspan="3">Late frost</td><td>Dates of last and first frosts (T < 0 °C)</td><td colspan="4">Dates of last frost in spring and first frost in autumn</td></tr>
<tr><td>Number of frost days (T < 0 °C)</td><td colspan="4">X
From March to April</td></tr>
<tr><td>Minimum temperature reached per fortnight</td><td>X</td><td></td><td></td><td></td></tr>
<tr><td rowspan="4">Rainfall and drought</td><td>Cumulative annual precipitation</td><td colspan="4">x</td></tr>
<tr><td>Maximum of precipitation sum over 3-days: problematic if above 30 mm</td><td>X</td><td>X</td><td>X</td><td>X</td></tr>
<tr><td>Maximum number of consecutive dry days per season (P = 0 mm)</td><td>X</td><td>X</td><td>X</td><td>X</td></tr>
<tr><td>Number of days with P-PET < 0: problematic if above 4 weeks</td><td>x</td><td>x</td><td></td><td></td></tr>
<tr><td rowspan="2">Heatwaves</td><td>Duration of heat waves: defined as periods where daily Tmin > 18 °C and Tmax > 32 °C for at least 4 consecutive days</td><td>x</td><td>x</td><td></td><td></td></tr>
<tr><td>Number of heat waves during the season</td><td>x</td><td>x</td><td></td><td></td></tr>
<tr><td>Winds</td><td>Speed peaks and directions.
The frequency, and directions, of winds above 65 km/h expected per year</td><td colspan="4">X</td></tr>
<tr><td>Soil moisture</td><td>Standardised Soil Wetness Index (SSWI)</td><td>x</td><td>x</td><td>x</td><td>x</td></tr>
<tr><td>Climate analogous spaces</td><td>Agricultural areas (and practices) that are currently coping with the (near and distant) future temperatures and rainfall conditions expected in the Parisian region.</td><td>x</td><td>x</td><td></td><td></td></tr>
<tr><td>Urban planning regulations</td><td colspan="5">Urban regulations on the location and characteristics of greenhouses and tunnels and the construction of agricultural buildings.</td></tr>
</table>

*Thresholds considered as problematic by farmers are indicated in the case farmers mentioned them (but farmers did not provide thresholds for every variable).

While air humidity is not a relevant variable for farmers' strategic decisions, precipitation and drought are addressed together to signal meteorological droughts for short-cycle vegetable crops. Farmers request information on low precipitation and drought, indicated by the maximum of precipitation sum over 3 days exceeding 30 mm, as a threshold beyond which precipitation is useless, in addition to cumulative annual precipitation, maximum number of consecutive dry days (P = 0 mm) per season and number of days with P-PET < 0 above 4 weeks. With regard to the crops' growing season and water requirements, the cumulative annual precipitation alone does not necessarily indicate for farmers an adequate distribution of precipitation. Combining the cumulative annual precipitation with the maximum of precipitation sum above 30 mm over 3 days provides additional information on water received in excess, lost in runoff, and thus helps to indicate irrigation requirements for farmers.

Additional needs in terms of climate information

Farmers also express additional needs in terms of wind speed peaks and directions, soil moisture, climate analogous spaces.

Wind is a major parameter for the energy sector (Howland et al., 2019) and a usual one for agriculture to monitor windstorms. In our case, information on wind speed peaks and directions is mainly needed to help decide whether to invest in (high) tunnel-based production and, if so, what their orientation should be. This variable is all the more important given the high cost of these artificial climate shelters. From the adaptation perspective, farmers are interested in knowing the annual frequency, and directions, of winds over 65 km/h. According to farmers' expertise, winds above a certain speed cause crops to dry out and, beyond the 65 km/h threshold, are likely to damage shelters, especially high tunnels. Climate information on wind speed peaks and directions is requested in conjunction with late frost projection (see next section).

Soil moisture is similarly an additional variable requested by farmers in conjunction with high temperatures, low rainfall and drought, climate analogous spaces and thermal amplitudes (see next section). It is an important variable in land–atmosphere feedback (Tawfik and Steiner, 2011) and a key parameter for sowing, planting and irrigation management decisions, especially in water-limited areas. Within the ClimSec project (Vidal et al., 2012) a Standardised Soil Water Index (SSWI) based on agricultural drought is available on the DRIAS portal to analyse the effect of climate change on agriculture. The soil moisture product also exists in other climate services such as *Clisagri*, using the Standardised Precipitation-Evapotranspiration Index (SPEI) (Ceglar and Toreti, 2021) or within the Copernicus Climate Change Service (C3S) using the Soil Water Index (SWI) to quantify the moisture condition at different depths in the soil. Seasonal predictions for spring and summer soil moisture may indicate the effects not only of increased frequency and duration of future droughts and heat waves, but also of increased temperatures and evapotranspiration. With regard to the data projected by the selected GCM/RCM couple, farmers pointed out that the increase in evaporatranspiration together with rising temperatures, is not offset by rainfall, which tends to be stable or even decreasing in summer. Requested by farmers during the workshops, soil moisture is a plot-level witness of the impact of climate change on soils and irrigation needs.

Farmers require analogous spaces to explore adaptation options

Farmers also requested climate analogous spaces (or sites) for future summer and spring seasons. The concept of climate analogous spaces (Hallegatte et al., 2007; Kopf et al., 2008) was introduced by Parry and Carter (1989) and Darwin (1995) to assess the impacts of climate change on agriculture. From the point of view of the simulated future climate, an analogous space is one where the current climate corresponds to the simulated future climate. The analogous climate approach aims to identify current areas in the world that have a climate similar to that predicted by the climate simulations in a given area. To get as close as possible to warmer and drier (unexperienced) future conditions, farmers asked which areas are currently experiencing the climate conditions they are likely to face in the future? This information is intended to anticipate adaptation strategies in the Parisian region by visualizing those already in place in analogous areas. Climate analogous spaces are a product of growing interest within agriculture-related climate services, for example the CCAFS[12] Climate portal (https://ccafs.cgiar.org/node/19757) (Navarro-Racines et al., 2020). In our case, farmers require "seasonal analogous spaces" for summer and spring in particular, in order to learn about new seed species or varieties, or locally applied cultivation practices in analogous areas. As an example from our workshops, farmers asked whether future summers would look like the current summers in Athens or Seville, and whether future springs would look like the current springs in Toulouse, etc.

Farmers raise an information need on urban planning regulations. The final set of climate-relevant information also covers a non-climate variable, namely urban planning regulations. Climate services need non-climatic inputs in order to provide information on non-climatic factors that influence climate change impacts (Räsänen et al., 2017). Integrated climate services with non-climatic data such as land cover, atmosphere, ground, soil conditions, and socio-economic soil data are usually required in the case of forestry (Fraccaroli et al., 2021). For the vegetable sector, urban planning regulations represent climate-related information that may influence a fundamental adaptation option, namely the implementation and characteristics of greenhouses and tunnels. A possible change in planning regulations with respect to greenhouses and tunnels would significantly alter the overall range of climate-relevant variables and thresholds. In our case, the construction of agricultural buildings, be they for plant production, material storage or animal shelter, is subject to particular regulations. Depending on their use and their dimensions, greenhouses and tunnels are subject to conditional authorisation, location, floor space and height rules under the regulations of the PLU (local urban plan).[13] During the workshops, farmers raised the fact that tunnels and greenhouses can play a key role in adapting to late frost and heat waves. Constraints on the orientation and the heights of greenhouses/tunnels have an impact on the radiation variable. In addition, the roofs of the greenhouses are used for rainwater harvesting. In the Paris region, changes in urban planning regulations are all the more crucial as they occur in parallel with the ongoing trend towards diversification from arable to vegetable crops. This trend is naturally accompanied by the creation of greenhouses and new farm buildings. Peripheral areas have traditionally been subject to urban pressures and urban planning constraints, with rural activities shrinking as a result of metropolisation processes (Vanderlinden and Touili, 2022). Initially required by the farmers of the "Plateau de Saclay", urban planning regulations were subsequently considered as relevant climate information by the three selected areas of the Parisian region.

Toward tailored climate services adapted to the peri-urban context of the Parisian region

To adequately inform decision-making and adaptive responses, non-climate information (e.g. here urban planning regulations) appears to be a necessary complement for climate services (Lourenço et al., 2016; Räsänen et al., 2017). The context-specific nature of vegetable farming in the Parisian region can help to interpret and understand why these specific needs exist (Table 4). Our analysis shows that in the Parisian region context, the tailored needs are shaped by farmers' access to water, by the Parisian demand market, and by *peri*-urban geographical locations constraining the possibilities of sheltered production.

Farmers' needs are strongly influenced by the challenge of access to water for agriculture in peri-urban areas

Monitoring water needs for irrigation seems to be of paramount importance to balance excessive temperatures (Table 4). In addition to being a production factor, water is also an adaptation factor that enables farmers to irrigate in response to excessive temperatures, whether very high (heatwaves) or very low (severe frosts), according to our results. While most farmers have access to (underground) water sources, such access is not unlimited. Whereas water availability was not a concern in the past, vegetable farmers observed an increase in the number of irrigation water restrictions in recent years, especially in *peri*-urban areas where agriculture and cities compete for water access. The French government's launch of the "Varenne Agricole de l'eau" in autumn 2020, focusing on the prospects for water and agriculture by 2050 in the context of climate change, had raised farmers' concerns about this issue. Furthermore, the projection data from the selected GCM/RCM couple suggest that, in parallel with stable annual rainfall, increases in temperature and evapotranspiration (especially in summer and spring) lead to increases in crop water requirements. The request for combined information on thermal amplitudes, soil moisture, rainfall and high temperature is so that "extra" water demand for irrigation can be anticipated. For farmers, water needs are likely to increase. Thus, meteorological and agricultural droughts are indicated by trends in soil moisture and low rainfall/drought, making it possible to anticipate investments in the most suitable irrigation systems and water reservoirs.

Table 4
The interrelated climate, and non-climate, information requested in order to visualise a climatic situation within climate services.

The preliminary climate-relevant variables	Additional information required by farmers	Why?
High temperatures	Soil moisture Low rainfall and drought	To indicate "extra" water demand for irrigation for spring and summer seedlings and leafy crops, and thus anticipating water resource solutions (e.g., water reservoir types and volumes, efficient irrigation systems, etc.) with respect to future meteorological and agricultural droughts.
	Climate analogous spaces	To explore the transposition in the Parisian region of (new) practices (crops, seeds, etc.) and drought-resistant varieties from warmer and drier analogous spaces
Mild temperatures in winter	Thermal amplitudes (Tmax-Tmin)	To indicate heat stress impacts on plant growth, especially due to (day and night) temperature differences.
Late frost	Thermal amplitudes (Tmax-Tmin)	To monitor the risk of pests (flea beetles for tomatoes, aphids for aubergines, etc.) and weeds.
	Urban planning regulation	To know in advance whether it would be possible in close cities to expand greenhouse-based production that allows for early sowing while coping with late spring frost.
	Wind speed peaks and directions	To anticipate investments in the most suitable characteristics (material, reinforcement, height, etc.) and orientation of high tunnels with respect to wind speed peaks and direction.
Low rainfall	Drought Soil moisture	To assess whether annual rainfall, and thus groundwater reserves, are likely to support additional withdrawals (through irrigation).
	Analogous spaces	To explore the transposition in the Parisian region of (new) practices (crops, seeds, etc.) and drought-resistant varieties from warmer and drier analogous spaces
Heat waves	Soil moisture	To indicate "extra" water irrigation due to more extreme deficit
	Urban planning regulation	To know in advance whether it would be possible to invest in higher tunnels to cope with the higher evapotranspiration and water stress in the open fields.

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[12] CCAFC (Climate Change, Agriculture and Food Security).

[13] https://www.senat.fr/questions/base/2018/qSEQ180203290.html.

Our workshops' results outlined water rarefaction as a marker of the impact of climate change at the scale of the Paris region. A new component of the French climate services, DRIAS-Eau (https://www.drias-eau.fr/), is in the process of developing hydro-climatic projections of water resources (average annual and seasonal water availability) and hydrological extremes. The regions with the wettest soils on average today could experience the greatest changes compared to the current climate (Vidal et al., 2012). Farmers are becoming aware of the trend towards economies in terms of future water withdrawals, which explains the additional needs mentioned in Table 4. The availability of water resources, absolutely essential for vegetable farming, is even more crucial given the multiple domestic/urban, agricultural, industrial and recreational uses of water in the Parisian region.

Farmers' needs are shaped by the specificities of the urban vegetable market demand

In parallel with air temperatures and rainfall, late frost are becoming highly relevant due to the Parisian market demand and *peri*-urban geographical locations.

On the one hand, farmers expect to have to deal both with mild (warmer) winters (and therefore earlier crop maturity) and late frost (and therefore a threat to yields). Late frost is not necessarily a major threat, since it arises from early sowing dates. Yet it is becoming a considerable threat, because the earlier production dates that farmers seek are driven by the Parisian market demand. In case of short circuit, the latter requires earlier production to meet local demand and consumer choices in a context of competition from national and/or international products. Summer is almost a standstill, as demand from collective catering, open air markets or even supermarkets declines. This implies crucial deadlines for the end of production (around 15 June) and renders the April late frost a relevant variable, especially for farmers involved in direct sales. For the latter, the challenges of adapting to climate change lie at farm level and beyond, in marketing fresh (and perishable) products at the right time of year. The Parisian demand influences farmer's decisions and therefore, interfere with their needs of climate information.

Information of urban planning is specifically required to adapt to climate change in peri-urban areas

The growing demand for local products close to cities is also putting agriculture, and market gardening in particular, at the center of territorial stakes. The integration of short-distance farms brings advantages, in terms of local food offer and demand, but also constraints for farmers, notably those related to the ongoing urban expansion that has already reached part of the "Plateau of Saclay" agriculture areas. Urban and landscape constraints regarding the implementation of shelters, particularly high tunnels, and their integration into the landscape, are a specific feature of *peri*-urban farming activities. Regulatory constraints on covered surface areas and height of tunnels/greenhouses already exist and are likely to increase as a result of the urban expansion of the Greater Paris Metropolis. Almost all farmers have less than 10 % of their land covered, which they hope to expand especially for winter vegetables sown in June. Additional non-climate information about how urban planning regulations will evolve in *peri*-urban areas of the Parisian region thus become relevant. These arguments explain the additional requirement of access to urban planning regulations, to know in advance about the future of greenhouse-based production that represent a major adaptive measure.

While addressing user needs is fundamental for climate services to guide adaptation strategies more successfully, an in-depth understanding of why these (specific) needs exist is equally important. For a tailored climate service for vegetable farming, it appears that the *peri*-urban context of the Parisian region is largely shaping particular requests, in our case.

Conclusion

This paper looks at local climate change impacts the agricultural subsector of vegetable production. Its results support the growing emphasis on bridging the gap between the provision of climate information and the users' needs at a given spatial scale. In this section we consider some observations about our participatory process as well as our results.

The main result of this paper is that it highlights the need for a tailored climate service for the vegetable sector at the scale of a *peri*-urban area such as the Parisian region. As this result is the outcome of a participatory process, it is important to underline some points on the process itself.

First, economic and/or social conditions can create subcategories of stakeholders and thus vary the climate information needed for adaptation to climate change. For instance, within the same group of workshops, young organic farmers who, with limited farmland, had specialised in vegetable production and made it their sole source of income (as vegetables are not combined with cereals) were the most sensitive to certain variables such as late frost, soil moisture and low rainfall, and to the relevance of climate projection into the distant future (2041–2060). Furthermore, and for the same geographical area, the climate-relevant information is likely to vary according to the local administrative area, taking into account urban conditions and/or urban planning policies. Among the three workshop groups, the farmers of the "Plateau de Saclay" were particularly sensitive to the relevance of the urban, non-climatic dimension in their adaptation strategies.

It is also worth noting that the larger the number of participants, the less effective their individual participation was during the workshops. The time ratio per participant over the total duration of the workshop was indicative of the fact that discussions and interactions were monopolised less in workshops with few participants (e.g., Le Mée-sur-Seine). In our case, the final synthesis workshop proved to be very useful in this respect, as it brought farmers from all three areas together for a further session. A large attendance of farmers is not always synonymous with effective participation and collective decisions. Post-workshop individual surveys could help to overcome this bias of silent minorities during workshops, to ensure more collective decisions. The participatory process could also have benefited from the involvement of additional representatives, such as local elected officials and hydrological or climate experts, in addition to agricultural experts and farmers.

The results of this paper reveal a need for both climate and non-climate information for vegetable farmers in order to adapt to climate change.

On the one hand, some of the requested climate information seems to act as an early warning threshold, such as maximum wind speed values per day, and it is not available on the DRIAS portal (only mean diurnal wind speed is available). The same applies to information on analogous spaces, which are likely to be plural, depending on the climate variable under consideration (i.e. maximum temperature, temperature ranges, rainfall). Their usefulness is likely to be limited due to differences in soil types and properties, and due to consumer choices and market demand that which new crops should be included and which should be dropped, as well as cropping calendars. To provide this information, national climate services need to extend their scope to international high-resolution data, or develop partnerships with other regional climate services. Other hydro-climatic variables that were mentioned in our workshops may also be part of the climate-relevant information. These are the "extra" water for irrigation index and the groundwater availability forecasts on annual scales. Likewise, the "radiation" variable mentioned in only one of the three workshops was not retained as a climate-relevant variable for the vegetable sector in the Parisian region.

On the other hand, the concept of a climatic situation and the need for non-climate information calls into question the responsibility of the climate services in this respect. The demand for non-climate information does exist. This non-climate information could be considered within climate services or in other services to complement climate services, to provide useful information for users to adapt to climate change. The growth of demand-driven climate services raises the question of the boundaries of the climate services domain, and the extent to which other non-climate factors can be integrated, even if these are evidenced through participatory efforts towards matching the supply and demand for climate services. Can we question the logic of “supply and demand” according to which climate services conceive of climate information as a “product” designed to meet a “demand”? Given the difficulty of broadening the scope of expertise in climate services to include non-climate variables, it would make sense to broaden the categories of stakeholders involved in participatory workshops. Various end-users and high-level decision-makers could be closely involved in the co-production of content for climate services. This is probably due to the fact that the adaptation of vegetable farmers is influenced by many other stakeholders beyond the farm level, so the process of identifying farmers’ needs should involve local elected representatives, hydrological experts and water resource managers, land-use planners, as well as food system actors.

What emerges from our study is that “raw” climate information needs to be translated into agricultural impacts, not only for farmers’ decision-making, but also for several higher-level end-users and decision-makers (such as government officials and local authorities) to enable them to anticipate public policy changes. A tailored climate service for farmers seems to go beyond the farm and purely agricultural issues, to encompass water management organisations and stakeholders, the local market, and the ongoing metropolisation of the Parisian region. Can we expect to see the emergence of an integrated “urban and hydro-climate services” to meet the vegetable farmers adaptation needs?

CRediT authorship contribution statement

Nabil Touili: Writing – review & editing, Writing – original draft, Validation, Methodology, Formal analysis. **Kevin Morel:** Writing – review & editing, Writing – original draft, Validation, Methodology, Formal analysis. **Christine Aubry:** Visualization, Supervision, Project administration. **Natalie de Noblet-Ducoudré:** Visualization, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The climate projection data used in this paper are available on the portal of the French climate service DRIAS

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