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ORIGINAL ARTICLE

A modelling and participatory approach for enhancing learning about adaptation of grassland-based livestock systems to climate change

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Abstract To anticipate local livestock systems' adaptation to climate change, we created a modelling and participatory approach that relies on the development and use of agro-meteorological and agronomic supports that are based on climate- and plant-model outputs and shaped by a conceptual model of a livestock system. The objective of this paper was to examine the extent to which the approach, in particular the use of the supports in workshops with farmers and advisors, helped to stimulate learning about adaptation options of livestock systems to climate change and the way in which workshop discussions can improve researchers' conceptual models of livestock systems. We show that the use of supports can generate incremental adaptation options (interpreted as single-loop learning) and sometimes more radical ideas for change (interpreted as double-loop learning). Subsequent analysis of workshops provides new insights into livestock systems (e.g. considerations used by farmers for key decisions). We demonstrate that this modelling and participatory approach avoids the trade-off often found between the credibility of livestock-system adaptations to climate change and their relevance in practice.

Keywords Land use · Farmer · Grassland · Boundary object · Workshop · Knowledge · Pyrenees

Introduction

When applied to agriculture, studies of climate change consist of evaluating its impact (i.e. answering "what if?" questions) or mitigation and adaptation options (i.e. "what to do?" questions). Many studies have relied on assessing the impact of climate change on biophysical processes such as plant growth (e.g. Zhang et al. 2007) and on defining options to enhance mitigation. However, defining adaptation options is a challenge for which agricultural science remains in its infancy (Meinke et al. 2009). Indeed, few studies have addressed the adaptation challenge (e.g. Rivington et al. 2007; Martin et al. 2011a).

Defining adaptation options at the farm level is a complex task for at least three reasons:

- livestock systems are composed of multiple components (e.g. soil, plants, animals) that interact in a nonlinear way in response to farmers' activities (Darnhoffer 2010)
- adaptation options must be designed to cope with a range of future scenarios that integrate driving factors besides climate change (e.g. socio-economic ones), and our understanding of the dynamics of such factors is limited (Smit et al. 1999)
- adaptation is highly context dependent because the agro-ecological characteristics of regions (e.g. spatial heterogeneity of soil type, altitude and climate; farmers' goals, assets and access to markets) require that adaptations be tailored to local conditions (Hansen et al. 2009).

One consequence of such complexity is that the objective of adaptation-related research at field and farm scales is not to produce generic and certified knowledge or ready-made solutions (Smit and Wandel 2006) but rather to

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improve the adaptive capacity of farmers and other agricultural stakeholders to cope with change and uncertainty (Darnhoffer et al. 2010). This approach requires learning (Collins and Ison 2009; van Mierlo et al. 2010) about climate change, its impacts and possible adaptation options. This learning concerns both agricultural stakeholders and researchers. Stakeholders know best whether or not adaptation options are actually appropriate (i.e. important, feasible and acceptable for their conditions). Researchers alone cannot anticipate all aspects of adaptation but are well placed to facilitate stakeholder learning.

Adaptations can be incremental, through more efficient use of available production resources and/or modification of management strategies (March 2006). This type of adaptation requires single-loop learning (Argyris and Schön 1996). However, to adapt livestock systems to simultaneous changes in climatic and socio-economic driving factors, incremental adaptation may not be sufficient (Ash et al. 2008). The system may require greater change, involving relinquishing basic certainties, goals and values as well as fundamentally revising the problem definition, perceived solutions, production paradigms (March 2006) and, as a consequence, management strategies. Therefore, new configurations of production resources need to be explored, which requires full system understanding (Howden et al. 2007). Such revision corresponds to double-loop learning (Argyris and Schön 1996). Levels of learning involve increased understanding of the situation in each successive loop.

Stakeholder learning about climate-change adaptation can be stimulated through discussion workshops (e.g. McCrum et al. 2009) or by coupling workshops with the use of agro-meteorological and agronomic supports (e.g. Matthews et al. 2008) or such as whole-farm models (Rivington et al. 2007). With the latter approach, stakeholder discussions occur before and after the modelling phase to define the topics to be addressed and to interpret outcomes. Such an approach is well suited for evaluating the impact of climate change. When choosing appropriate adaptations, a potentially better approach is to define adaptations during discussions. This approach relies on the use of simpler models than those in the previous approach, which often appear as a black box for non-researchers. In this way, the models and their outputs can be easily communicated with and used by/with the stakeholders involved. As part of this approach, we postulate that it is more appropriate to restrict the use of models to the field scale (e.g. supports for the soil-plant-atmosphere system in our study) and to address the farm scale through discussions (Martin et al. 2011a).

One objective of this paper was to present the development and use of agro-meteorological and agronomic supports in workshops and to show how they helped stimulate farmer and advisor learning about climate-change adaptation options for beef- and dairy-cattle production systems that are mainly grassland-based (i.e. they can include forage crops). The second objective is to use the discussion process to improve our own conceptual model of grassland-based livestock systems to plan further supports. When implementing the approach, researchers, farmers and advisors are expected to adopt a forward-looking (anticipatory) attitude towards learning (Tschakert and Dietrich 2010) to seek adaptation options to cope with future climate issues. We first present the conceptual framework used for preparing and running the workshops and using their outputs, determining the case study and developing supports. Second, we examine the use of supports during participatory workshops. We then analyse farmer and advisor learning, the way in which this approach enriched the conceptual model used for studying livestock-farming systems and the role of the different types of supports.

Materials and methods

Overview of the approach

To stimulate scientific output and real-world outcomes regarding climate-change adaptation options, discussion is necessary among farmers and/or agricultural advisors, as is reflective analysis among researchers (Fig. 1). Therefore, we have combined modelling with farmer and advisor participation. Modelling biophysical processes guarantees credibility of scientific knowledge production (i.e. scientific adequacy) but may be inappropriate for a local context, especially if models are only science-driven (Sturtevant et al. 2007). As participatory approaches are generally case-specific, they are relevant to stakeholders' concerns and contexts. They also provide fair and unbiased information that respects stakeholders' values (i.e. "legitimate"; Nassauer and Opdam 2008). However, participatory approaches alone can neglect relevant knowledge or technical innovation from agricultural science (Spinuzzi 2005). Our idea was thus to build learning supports using simulation models of soil-plant-atmosphere systems and then apply them in workshops. As it avoids the weaknesses of both approaches, the resulting combination of modelling and stakeholder participation appeared relevant to our objectives. Consequently, we built cognitive tools which generated situations (i.e. system states and outputs) that workshop participants could compare with their tacit representations. The tools convey action-orientated expertise, preferences, values and beliefs (Eckert and Bell 2005), but their application relies on careful workshop design and preparation (McCrum et al. 2009).

The agro-meteorological and agronomic supports developed fulfilled the role of "boundary objects", which

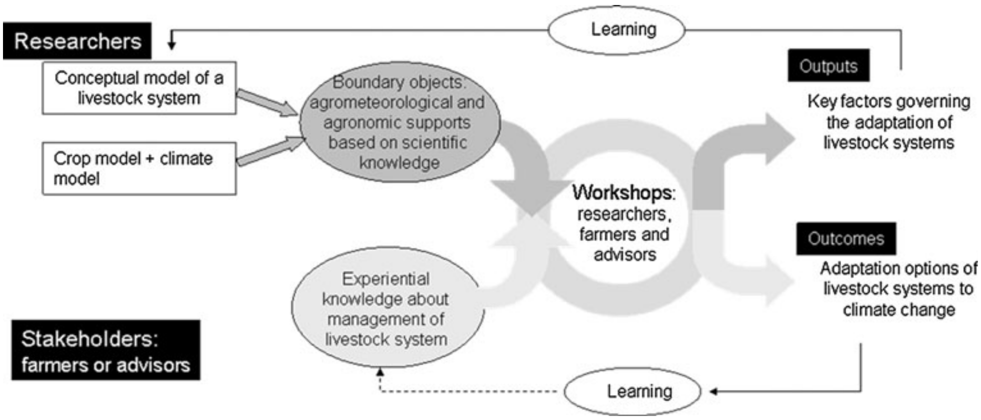

Fig. 1 Framework of the approach (*dotted line*: feedbacks that are not considered in this study)

“simultaneously inhabit independent but intersecting social worlds and are flexible to the needs of multiple stakeholders” (White et al. 2010). The presentation and use of these supports was expected to encourage information exchange and dialogue among stakeholders and to provide relevant feedback for researchers (Holman and Harman 2008) (Fig. 1). Two main types of support were designed. One was informative, tailored to trigger responses from farmers and advisors. We expected that these supports would encourage learning due to the novelty of the information presented, in this case about the local impact of climate change on forage production. Another support was interactive, tailored for use by farmers and advisors to facilitate the representation of the system in which they considered future adaptations. We expected that the new climate features provided in these supports would enhance the creativity of workshop participants when designing suitable livestock systems.

Information exchange around the presentation and use of these supports relied on combining different types of knowledge, which is necessary for generating outputs and outcomes (Raymond et al. 2010). Farmer and advisor experience-based knowledge includes farm management, which aims to allocate resources over space and time to meet specific objectives (e.g. production, environment or labour) that have local and practical value. Scientific knowledge about farm management involves general principles that structure the functioning of grassland-based livestock systems. These principles shaped the supports used in workshops. The livestock-farming-system approach considers the farmer, animal herd, grasslands and forage resources as a whole system and accounts for interactions among them, especially in response to land-use allocation and feeding management (Duru and Hubert 2003). Specific attention focused on at least four critical elements that influence how farmers organise and manage their livestock-farming systems:

- balance between the availability of grazable herbage or other feed resources (e.g. hay) determined by land-use allocation (e.g. partitioning between cutting and grazing; Fig. 2a) and feed requirements to attain animal-production targets (Fig. 2b) (Sheath and Clark 1996)
- interdependence between key decisions for land-use allocation and management (e.g. fertiliser application, grazing intensity) and feeding-management decisions (e.g. grazing dates, silo closing and opening dates; e.g. Gray et al. 2003), which may affect the range of adaptation options
- diversity in various forms (e.g. grassland type, forage crops, field characteristics, number of animal mobs) since it plays a key role in the strategies of farm households in coping with change and uncertainty (Darnhoffer et al. 2010)
- seasonal variability in herbage availability for a wide range of grasslands and management regimes, including factors that govern field accessibility in addition to forage production and nutritive value (Fig. 2c; Andrieu et al. 2007).

Case study and development of agro-meteorological and agronomic supports

Case study

Application of the approach occurred within a research project aimed at assessing the vulnerability of grasslands and livestock-farming systems in France and elsewhere in Europe to climate change and extreme events. Typically, when dealing with short-term adaptations, farmers and advisors tend to discuss small changes to farm structure and management. The 2050 time horizon was chosen because considering long-term adaptations encourages stakeholders to propose more substantial changes and increases the chances that farmers will realise their potential benefits.

The south of the Midi-Pyrenees (France) was chosen as a case-study region to develop and discuss climate-change

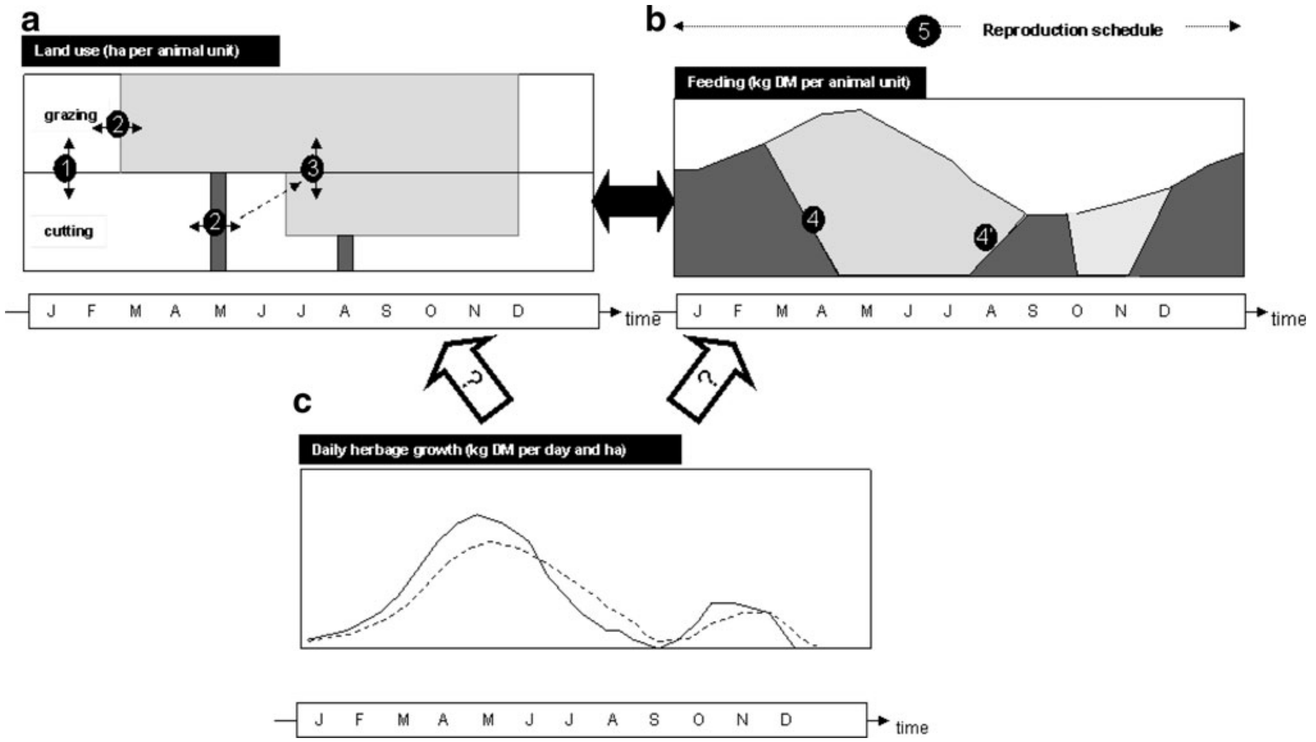

Fig. 2 Land use (**a**) and animal-feeding budget and reproduction schedule (**b**) as components of a conceptual model of livestock system. An example of support presenting plant growth rate for the current (*dotted line*) and future (*full line*) climates is given in **c**. Areas in *light grey* and *dark grey* correspond, respectively, to grazing and cutting (**a**) and to feeding from grass or feedstuff (**b**). *Numbers encircled* indicate key management decisions; the *dotted line* indicates interdependence between decisions. *Arrow* with "?" means how plant growth curves can be used for understanding how farmers will change their land and herd management to adapt to climate change

adaptation options in livestock-farming systems. Three specific locations were selected (Fig. 3):

- Ercé (42°51′01″N, 1°17′25″E, 700 m a.s.l.), located in the Pyrenean mountains. Farms are beef-cattle production systems based on semi-natural grasslands practising long-distance transhumance to higher ground during summer.
- Saint Girons (42°59′09″N, 1°08′48″E, 350 m a.s.l.), located in the Pyrenean foothills. Farms are beef- and dairy-cattle production systems based on grasslands (e.g. grass-legume mixtures) and forage crops (e.g. silage maize).
- Toulouse (43°36′16″N, 1°26′38″E, 150 m a.s.l.), located in the Garonne River valley, was used as a reference to compare its current climate to that at Saint Girons between 2035 and 2065.

Climate data (temperature, rainfall, potential evapotranspiration (PET)) were recorded from a database of past climate conditions (1980–2009). In the current climate of the study area, the water deficit is lower in the mountains

Fig. 3 Map indicating the studied locations in the south-west of France (http://www.cartes-de-france.fr)

than in the foothills, mainly due to the annual rainfall (1,600 and 1,100 mm, respectively) and rainfall distribution (uneven throughout the year in the foothills). For future climate conditions, downscaled (8 × 8 km) precipitation and temperature projections based on the IPCC A1B SRES scenario (IPCC 2007) were used (see Pagé et al. 2008 for further details).

Informative supports

One major concern in our approach was to provide an adequate scientific information. Thus far, global circulation models have provided reliable predictions of climate-change trends. However, uncertainty in predictions of seasonal climate variability is high (Ganguly et al. 2009); so, we restricted the focus to climate-change trends by averaging climate data. Past and future weather summaries (average monthly temperature, rainfall and PET from 30 years of observations or predictions, respectively) were generated for the three locations. Preliminary analysis showed that the current climate for a lower location indicated the future climate for a higher location (Fig. 4a, b, intended for the workshops). We expected that this information would provide a relevant picture of local climate change for farmers and advisors. Other curves showed seasonal changes in temperature and water balance (=rainfall − PET, with negative values equalling "water deficits"; Fig. 5).

To design availability indicators for feed resources, we generated curves of cumulative plant growth for past and future climates. Each curve was generated for different grassland types (e.g. early-permanent, late-permanent, sown) or forage crops (e.g. sorghum) and management options (e.g. year-round grazing, hay-making once or twice before grazing) for a single soil type by averaging model-simulation outputs for contrasting annual weather patterns. Additionally, we indicated key changes in plant development and production (e.g. beginning of growth in spring, maturity rates) between past and future climates because of their effects on land-use allocation and feeding management (Fig. 2).

To simulate the daily herbage growth, we used the modified model of Duru et al. (2010), mostly recently described by Martin et al. (2011b). This model had previously been calibrated for the case-study area under current conditions using field-experiment and on-farm data (Duru et al. 2009, 2010). Simulations of forage crops relied on the model of Brisson et al. (2003). To include the effect of increased carbon dioxide concentration in the air by 2050 on stomatal closure of plants, the calculation of radiation-use efficiency in the models was modified (Olioso et al. 2010). As in many studies (e.g. Zhang et al. 2007), no calibration was made to use the model under future climate conditions, as no empirical data exist for 2050. This limitation was explained to participants at the beginning of the workshop.

Interactive supports

Farmers and advisors are not always fully aware of the extent of differences in productivity, seasonality and feed quality of grassland types. Therefore, it seemed essential to make these differences and their consequences explicit in our boundary objects. Thus, using results from the same plant models (Brisson et al. 2003; Duru et al. 2010), we marked flattened wooden sticks with the available forage yield (kg/ha) per 4-week period of the year (called "forage sticks") for a wide range of combinations of grassland types and forage crops, up to three types of management options and two soil types (e.g. 140 and 60 mm of water reserves in the foothills). As accessibility to fields can be severely hampered by weather conditions, the model included constraints on field use related to soil-bearing capacity, expected rainfall and saturation deficit for successful in-field hay drying. It was particularly important that forage sticks indicate the quantity of forage realistically available rather than optimally attainable and represent it in a form that farmers use (i.e. kg/ha per 4-week period instead of daily growth). The forage sticks explicitly demonstrated the impact of climate change on grasslands and forage crops by 2050 (Martin et al. 2011a).

Workshop course and data analysis

First, the policy and socio-economic components of two IPCC scenarios (IPCC 2007) were adapted with regional experts and policy makers to the context of the study area (Martin et al. 2011a). Next, five workshops were organised with a different group each time, including either two or three farmers (four workshops) or four advisors (one workshop). Several participants had collaborative experience with the research team. Participants were chosen according to the location of their farm or working area (mountain or foothills) and their farm products or advisory domain (beef or dairy production). They were contacted by phone and informed about the objectives and workshop content. Workshops took place at a farm or local advisory office. Researchers prepared and led workshops according to a stepwise process (Table 1) to facilitate stakeholder involvement (Rivington et al. 2009) but did not propose farming-system adaptations, thereby remaining observers.

Participants were first asked what they knew about climate change and its consequences. We then presented the informative supports, which described the two scenarios in which climate-change adaptation options were to be developed. Participants used these supports to design land-use and feeding components of livestock systems adapted to the scenarios. Information provided through the supports became progressively more detailed and integrative, from annual and monthly weather summaries, to average herbage growth curves, to forage sticks indicating herbage

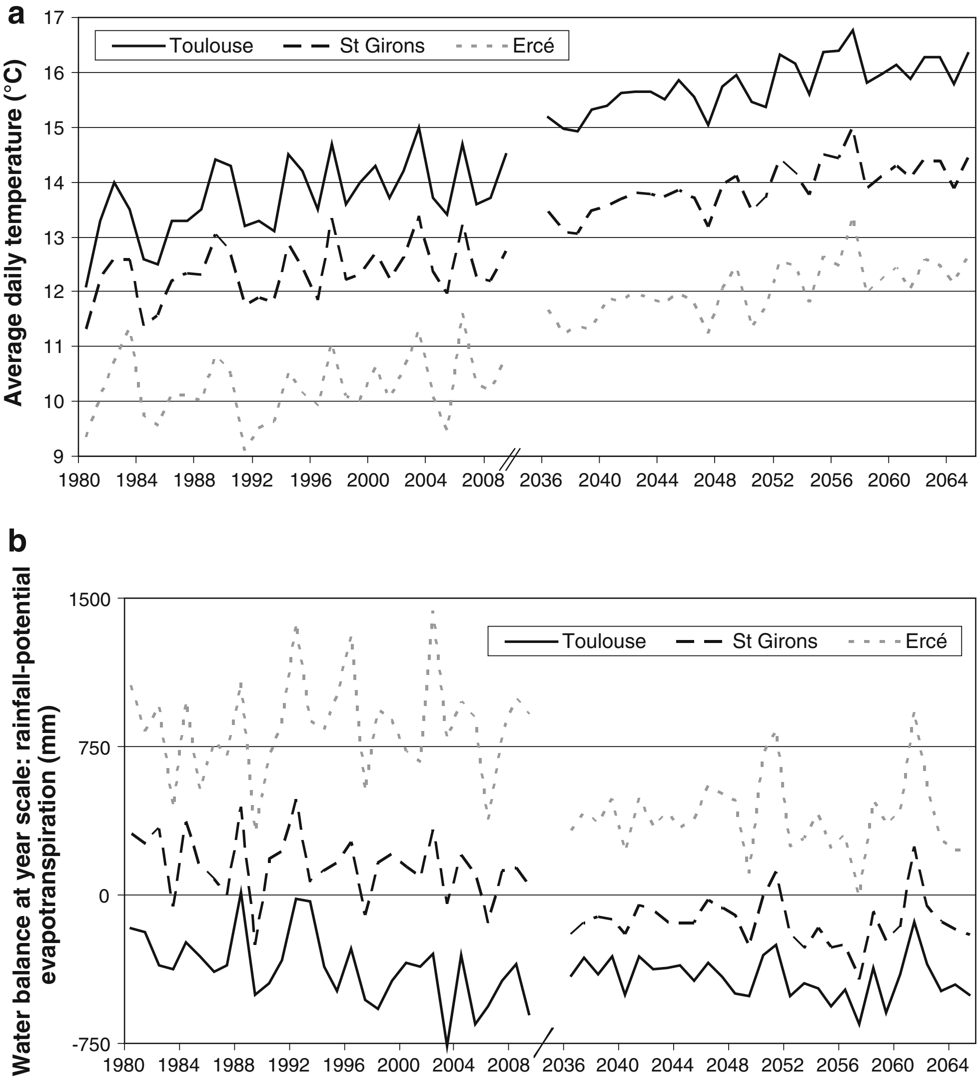

Fig. 4 **a** Mean annual temperature in the 3 locations (current climate: 1980–2010 and future climate: 2036–2066). **b** Mean annual water balance in the 3 locations (current climate and future climate)

Fig. 5 Monthly average temperature and water balance for an average year of past climate (*dotted line*) and future climate (*full line*) for foothills (St Girons station, 400 m asl)

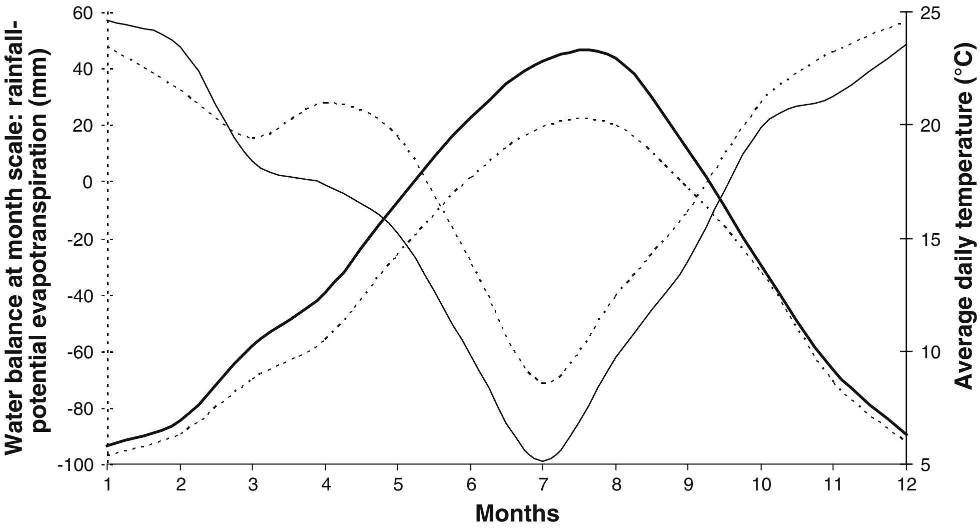

Table 1 Use of supports in workshops

Steps (tasks)	Description of the task	Support	Expected workshop outputs puts and outcomes
Introduction	Overall project presentation Ask views of participants about CC (perception a priori) *"What do you think about climate change?"*	No support	Knowing stakeholders' awareness of climate change and its potential impacts (before workshop)
Informative supports about climate change	Presentation and discussion around annual and monthly meteorological summaries *"What do you think of these data?"*	Three indicators selected by researchers according to their expertise as being relevant to stakeholders: meteorological summaries (average annual data for a series of years and monthly temperature and water-balance data) drawn within and between locations	Recording what farmers and advisors have learned about climate change and its impacts and their ideas for adaptation; recording of user's comments after presenting meteorological summaries after presenting plant growth profiles
Informative supports on climate-change impacts at field scale (soil-plant subsystem)	Presentation and discussion around agro-meteorological indicators *"What do you think of these data?"*	Yearly herbage growth profile for current and future climate, drawn on the same figure for each location	when using forage borders
Interactive supports for plant growth for a diversity of forage resources and field management	Presentation and use of interactive supports *"Design a grassland-based livestock-farming system adapted to 2050 context"*	Around 30 forage borders for a wide set of vegetation types and management practices for each location	

availability according to the plant type and management practices. We deliberately followed this incremental approach to facilitate progressive understanding, information use and learning and to provide the opportunity to discover participants' reasons for making particular choices.

One researcher acted as mediator, ensuring that the semi-structured workshop ran smoothly enough to record feelings, perceptions and ways in which the supports helped participants advance their understanding. Questions were open-ended to allow freely given responses and to limit the input and potential bias of the mediator's own beliefs. Workshop exchanges were transcribed from videorecordings and analysed to (1) examine what participants had learned about climate change and its impacts on local grassland and forage-plant growth; (2) capture the key factors that govern the adaptation of land-use allocation and feeding management to climate change in a given farm context; and (3) examine what we had learned about our conceptual model of livestock systems (Table 1; column 3).

Results

Perceptions of climate change at the start of the workshop

Farmers' perceptions of climate change varied greatly according to their location: "bad years" on the plains could be "good years" in the mountains. Farmers in the foothills seemed to have a clearer perception of climate change because the climate there is drier, and they had experienced severe droughts in the past (e.g. 2003). Additionally, they noticed that plant flowering was occurring earlier than it had 30–50 years ago. In mountainous areas, farmers were less aware of climate change as they were less exposed to drought and often considered climate change as a phenomenon occurring far away. Advisors had a developed awareness of climate change due to their global viewpoint and perhaps because they worked over wide areas with colleagues in other climatic regions. Some mentioned climate migration from southern regions to the north and from lower to higher altitudes, illustrating it by referring to tree-species migrations. Others observed a decrease in maize yields but were aware of other possible causes, such as permanent monoculture.

Use of supports during workshops

Initial informative supports showed farmers and advisors climate migration between locations on the basis of annual average temperature and water-balance curves. Over the past 30 years, temperature and water deficit significantly increased in the Garonne valley (Fig. 4a, b) but not in the mountains and foothills. Comparison between past (1980–2009) and future (2036–2065) climates confirmed that meteorological indicators will migrate from the plains

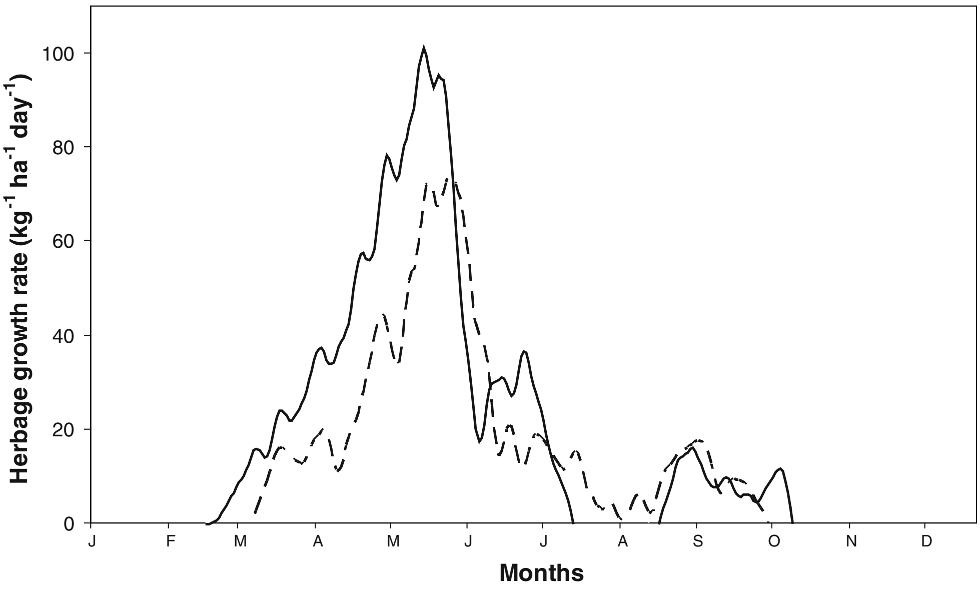

Fig. 6 Net daily plant growth rate of a grassland for past climate (*dotted line*) and future climate (*full line*) in foothills (St Girons)

to the foothills and mountains (Fig. 4a, b). Participants felt that it sent a clear message by highlighting changes in temperature and water deficit, the main climate factors that affect agriculture. A farmer from the foothills said, "*In the future, we will have the same climate as in Toulouse today*", and one from the mountains said, "*If the climate changes in this direction, we may have the same farming system as in the foothills*". This support enabled farmers to form an overall view of the climate that will shape livestock-farming systems by 2035–2065.

The next informative supports were monthly summaries of average temperature and water balance over 30 past and 30 future years (Fig. 5). Participants stated that there may be large increases in temperature and water stress in summer and smaller ones in winter. They predicted some potential impacts, such as low herbage production in summer, if plant species and management were to remain unchanged. One suggestion to reduce a summer forage deficit was expansion of management practices already in use (e.g. increasing the proportion of stored forage in animal feed, reducing area of summer crops). Others suggested more radical changes, such as diversifying the grassland types and forage crops currently grown and stocking fewer animals per hectare.

Informative supports based on simulated plant growth in past and future climates aimed to provide additional insights into how participants thought through the adaptation of land-use and feeding systems (Table 1). Compared to that in the past, plant growth in future clearly increased in spring, decreased in summer and, in the mountains only, increased in autumn (Fig. 6). In the foothills in future, periods with no plant growth decreased by 2 weeks in winter and increased by 5 weeks in summer (Fig. 6); a similar pattern was observed in the mountains. However, future annual herbage production was ca. 20% greater than in the past, mainly due to the increase in atmospheric CO_2 concentration. Farmers and advisors expressed surprise at these curves, as continent-scale predictions suggest decreased annual herbage production and increased drought. Their perceptions of climate-change impacts changed after viewing these curves. They stressed that although the future climate may increase annual production, the greater variability in seasonal production (e.g. longer summer period with no growth, more spring production) would be a major constraint. These changes in growth rates will shorten the grazing period unless deferred grazing is performed. Within this general framework, farmers suggested also considering spring field accessibility (related to soil bearing capacity) and snowfall frequency, which were not provided by the climate scenarios.

The interactive forage stick supports enabled experimentation and stimulated discussions between farmers and advisors, who spontaneously compared herbage production for combinations of grassland types and management options in past and future climates throughout the year. They observed that grassland types differed in their sensitivities to climate change, some (e.g. permanent grasslands growing in late spring) being more vulnerable than others (e.g. grass-legume mixtures), which can grow in early spring and in summer. Participants discovered that a combination of several grassland types on a farm can help cope with changes in herbage growth throughout the year. Experimenting with forage sticks encouraged participants to describe grassland types and forage crops in terms of assets (e.g. for feeding animals during drought) and constraints (e.g. for harvesting). These descriptions answered questions posed during previous stages, such as how to adapt to greater seasonal herbage growth: "*Here we need to think about the forage sticks*" (pointing to the spring period); "*They need to get ready to make up for another period when they'll need stocks*" (pointing to the summer period). Observing the high growth rate in spring, one farmer said, "*Watch out for too much grass growth in the spring because the cows won't eat it later*". Participants agreed on obvious adaptation options (e.g. earlier turnout dates for grazing, mowing) and sometimes suggested options not imagined earlier. For example, advisors proposed removing silage maize from animal rations or creating a second dairy herd, with calving in autumn, to match its peak milk production with the increased plant growth at that time. Participants discussed the ability of grassland types and feeding systems to meet the requirements of these proposals.

Discussion

Farmer and advisor learning

Many authors have observed the benefits of the participatory approach for farmers and advisors, as observed in our case study. For example, it created awareness of problems and new opportunities (Douthwaite and Gummert 2010) and increased farmers' choices of adaptive strategies (McCrum et al. 2009). Since the supports were not presented as end-products (Jakku and Thorburn 2010), for example entire livestock systems, participants were encouraged to translate scientific facts into adaptation options that met their own specific requirements (McCrum et al. 2009). Informative and interactive supports were thus used as intellectual companions to help make sense of problems and facilitate critical thinking about the biophysical system and ways to manage it (Jonassen 2000). However, the approach had two limitations. First, using pre-defined supports that fixed the domain to be investigated did not allow workshops to address all issues raised. Second, we were able to evaluate learning only by analysing comments made while using supports. Although some farmers claimed they would rethink their own system after the workshop, there is no guarantee that they will.

Farmer and advisor perceptions at the start of the workshops were directly linked to the exposure of their geographical areas to extreme events, such as drought, and to the magnitude of climate-change impacts on the kind of agricultural production that most interested them, as previously observed in alpine regions (Sérès 2010). Most farmers considered that high annual weather variability was a greater problem than long-term climate change. This opinion is similar to those observed in other countries (e.g. Australia; Pannell 2010), even though extreme events are less intense and frequent in temperate regions such as the one we studied. Farmers had few benchmarks for future climate conditions, and those they did have referred only to global changes, even though it is known that changes will differ among regions (Zhang et al. 2007). This finding was consistent with the analysis of farmer responses to climate change by Fleming and Vanclay (2010), who concluded that networking is the most appropriate tool for achieving a meaningful method to cope with the diversity of farmers' understanding and responses to climate change. Farmers often regarded extreme events and climate change as disasters but never as opportunities, which additional sources of information may allow.

For example, providing information at relevant temporal scales (e.g. seasonal) and successive use of informative and interactive supports enabled participants to absorb the information progressively, encouraging step-by-step learning. Informative supports provided coarse information (i.e. climate data, herbage availability) independent of forage or grassland types, while interactive supports enriched this information by providing production of forage and grazing resources for a wide range of plants, management options and growing conditions. This allowed participants to broaden their vision about the issue progressively and provide general solutions in the initial step. Afterwards, they provided context-specific options based on spatial and temporal constraints on land allocation for forage crops, grassland cutting and grazing, and functional relationships between forage production and animal-feeding requirements. The informative supports favoured the development of subsystem adaptations rather than whole-system adaptations (see Matthews et al. 2008), but these adaptations could be combined to create a variety of consistent whole-system alternatives. They also helped participants consider many forage resources and develop logical and substantive arguments (Bots and van Daalen 2007) with which to justify their choices. As they were designed as "bricks" to be combined with participants' experience-based knowledge, the supports did not force ready-made systems on participants. Being built for a wide range of environmental contexts, the forage sticks thus were considered legitimate by participants.

The supports helped participants create adaptation options at the livestock-system level that represented either single- or double-loop learning. The former included incremental adaptations (Ash et al. 2008), such as earlier turnout for grazing, mowing or growing drought-tolerant legumes. The forage sticks allowed participants to analyse the consequences of climate change critically. For example, farmers were able to detect situations to avoid: "*Leave* *plenty of grass standing when grazing in spring? I doubt that this will work.*" In contrast, double-loop learning led to more radical revisions that exploited opportunities generated by climate change, such as having a double herd with staggered calving periods to benefit from the higher autumn herbage growth. In addition, an increase in various forms of diversity was mentioned as an option to align management practices with soil conditions, reduce production costs in the current climate and cope with the increased variability in seasonal herbage production in future climate. These two types of adaptation conflict with the main trends that have been heavily promoted and implemented over the past 30 years: specialisation and maximising production (Darnhoffer 2010). When asked to design a system, participants can imagine adaptations and consider how to integrate them easily into a real livestock-farming system. This change in the understanding of system components increases the adaptive capacity of the system (Toderi et al. 2007), which reinforces the merits of addressing impacts at the local scale, as previously observed in New Zealand (Zhang et al. 2007) and France (Ruget et al. 2010).

A trade-off often exists between knowledge credibility, saliency (i.e. relevance to decision makers) and legitimacy (Cash et al. 2003), for example, when designing water-management scenarios (White et al. 2010). In our experience, using relevant boundary objects overcame this difficulty. Credibility was achieved by developing boundary objects based on sound science regarding the relationship between weather and plant growth. These boundary objects were used to assist participant learning (i.e. produce outcomes). Relevance is essential because participants designed livestock-farming systems by themselves, using the supports provided and their own experiences. In return, it helped to elicit tacit participant knowledge (i.e. outputs) (Raymond et al. 2010).

Researcher learning

The researcher who served as mediator sought to increase the quality of discussion. Instead of advising about options, the mediator encouraged farmers and advisors to explain their choices and share viewpoints. This enabled researchers to learn from the way participants used the supports. Workshops allowed researchers to validate the form and content of supports that they had previously defined with scientific knowledge. Furthermore, researchers improved their initial conceptual model of a livestock system by identifying key principles used by farmers to adapt their systems. For instance, we found that formal feed plans occurred at key periods for plants (e.g. low-growth periods) and animals (e.g. calving), as observed in other livestock systems (Gray et al. (2003).

The comments participants made while using the forage sticks highlighted the complexity involved in addressing adaptation of livestock systems to climate change because of the strong interdependence of system components and decisions made at different times of the year. For example, farmers stressed that increasing the grassland area cut in the spring (at the expense of grazing area) to reduce herbage surplus would likely lead to a dearth of grazing in early summer if mowing dates preclude reallocating mown plots to grazing. This imbalance would likely increase with the practice of meadow topping (i.e. early spring grazing that removes stem apices), which provides early grass but can delay mowing, thus exacerbating the dearth of grass for summer grazing. In general, farmers are careful to complete a feed budget in one season without jeopardising the next, as observed in other countries (Gray et al. 2003).

We recognise that the proposed approach in its current form is not yet able to cope easily with complex interactions among management decisions. In the light of this, we have defined management features to address in future:

- examine the relationship between land allocation (e.g. area allocated per animal unit) and management intensity (e.g. fertiliser amount)
- give equal importance to field accessibility and production because the lack of the former can upset the advantage of having more herbage available in a given season
- study the temporal relationship between sufficient herbage for grazing and stored-forage distribution.

Conclusions

Combining different support types is an educational approach that increases participant knowledge progressively when the issue is vague and not understood at a local scale. Supports help participants visualise potential environmental change and adaptations needed at a regional scale. The support types we provided shaped the design process, fostering certain adaptation options and excluding others.

The combination of modelling and participatory research successfully enhanced farmer and advisor learning about livestock-system adaptations to climate change. Before workshops, a dynamic model was used to build boundary objects at the field scale, such as herbage growth curves for a wide range of plant types and management options. This resulted in a range of feed resources tailored to the local context. Next, these boundary objects, not the model, were used in the workshop because they could be used in a tactile manner, as in a game. Participant learning entailed generating incremental adaptation options (interpreted as single-loop learning) and sometimes more radical ideas for change (interpreted as double-loop learning). Subsequent analysis of workshops provided new insights into livestock systems, especially regarding ways farmers plan key decisions and manage interactions between system components.

Using informative and interactive supports to scale up from the field to farm level was preferred over running a dynamic farm model (which needs more input data) as a black box during workshops. This approach provided insights into how to anticipate system changes on the field scale and use them to imagine possible adaptations at the livestock-system scale. Boundary objects and the method for using them in workshops are flexible enough for inclusion in an iterative and participatory cycle of discussion and feedback.

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