Knowledge elicitation and modeling of agroecological management strategies[1]

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Abstract
Agroecology applies ecological principles to the design and management of agricultural systems to improve environmental outcomes and livelihoods for farmers. However, little research to date has focused on cognitive tools that can facilitate the exploration, design, and increased adoption of agroecological management practices. This article is a preliminary attempt to develop guidelines to describe and bring to light the management behavior of farmers engaged in a participatory project of agroecological system design. Management strategies are explicitly defined using key decision-relevant concepts of activity, resource, goal, plan, and preference. These declarative structures make it possible to perform simulation-based experimentation of operational decision making at farm scale. The modeling framework facilitates the collective development and analysis of new management strategies in the face of knowledge gaps about the likely results of these strategies (especially highly innovative ones) and uncertainties about uncontrollable factors (weather in particular). Used in participatory workshops the presented approach supports learning, sharing and dissemination of agroecological knowledge.

Keywords Ecosystem services, Farming system design, Goals, Plans, Preferences, Adaptive management

1. Introduction

Agricultural producers operate in a dynamic and complex environment in which incremental innovation is a standard practice. However, environmental problems (e.g., pollution, reduced access to water, soil degradation), a changing climate, and shifting social demands are large contemporary challenges that may mean this "business as usual" approach is no longer sufficient. Specifically, agricultural producers may need to adapt to new contexts and, more likely, embrace a more profound or transformative change if they are to secure a future that is desirable, viable, and sustainable. The agroecological movement occurs in this transformation to more sustainable agriculture (Bennett et al., 2014; Caporali, 2015; Gliessman, 2015). Basically, agroecology is a farming approach that aims at making the most beneficial use of ecological processes within the agroecosystem to produce food and fiber in a sustainable and ethical manner (Altieri et al., 2015).

For many farmers, however, a rapid shift to agroecology is neither possible nor practical. Farming that relies primarily on the natural features of the agroecosystem requires new agricultural practices and management attitude (Sandhu et al., 2016). Farmers attracted by agroecology must be involved in active learning, (re)inventing technologies, and adapting their farming systems and habits. The transition from conventional agriculture to agroecology requires developing tools that can help analyze and design biodiversity-friendly production systems (Garbach et al., 2014; Duru et al., 2015) and practices that intentionally use ecosystem services (Haines-Young & Potschin, 2018; Martin-Clouaire, 2018; Dendoncker et al., 2018). Adopting, discovering, or implementing service-centered agroecological principles requires fundamentally different ways of designing, monitoring, and managing agroecosystems to consider specific features, such as a wide range of partially known and interacting ecological processes, several spatio-temporal scales, and the

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importance of farmers' cognition, as well as multiple social drivers (Duru et al., 2015). Farmers engaged in the transition process can, through professional awareness, experience, and intuition, distinguish what is unsustainable from what is at least more sustainable. Nonetheless, farmers need to understand agroecosystems in more detail by increasing their (i) biophysical knowledge about ecosystem functions (Zhang et al., 2007) and the functions' local expression, and (ii) management skills (Power, 2010), which help them make multiple decisions in interaction with agroecosystems to achieve desired production goals that are consistent with agroecological principles. Moreover, agroecological innovations are collective and integrative; they are typically based on the co-creation of knowledge, combining science with the traditional, practical, and local knowledge of producers (Duru et al., 2015).

Agroecology implementation is hampered by knowledge barriers relative to constitutive elements of practices. Knowledge may be missing regarding for instance the likely consequences of an action, its appropriateness regarding short- and long-term objectives, its compatibility with other actions, or its edge on alternative actions depending on the situation. Filling these knowledge gaps can emerge through a slow learning process of farmers based on evidence-based reasoning and critical thinking about their concrete personal experience with agroecological principles. The use of information and communications technologies (ICT) can greatly enhance and speed the learning process through more rigorous handling of various components and processes of agroecosystem, agroecology-focused and design-oriented discussions in groups of farmers, and computer evaluation of management alternatives in a dynamic simulation environment. Integrated simulation models contribute important insights to the analysis of farming systems. Simulation helps unraveling the complex and dynamic interactions and feedbacks among biophysical components across scales. It provides a framework for integrative contributions by functioning as learning platforms in participatory processes.

The objective of this chapter is to capture, in a modeling framework, the management strategies of farmers at a level of detail that enables the operational management process, (i.e., decision-making about and implementation of production-management actions) to be simulated. The approach adopted is inspired by the Belief-Desire-Intention (BDI) theory that provides a conceptual framework structuring the sequential decision-making behavior of rational agents. The theory was initiated by philosophical work of Bratman (1987) on practical reasoning (reasoning directed towards action) and further formalized and implemented by artificial intelligence and multi-agent researchers (Bratman et al., 1988; Pollock, 2006; Wooldridge, 2009). The BDI model states how agents decide, moment by moment, which actions to perform to pursue their goals consistently in time given their beliefs and values.

Although there are several simulation approaches developed to investigate agricultural systems (especially biophysical aspects) few are working up to farm scale (Power et al., 2011; Rotz et al., 2013) as in the present project. The objective is to enable deep exploration of whole-farm management aspects including planning of production activities, goal-based adaptation to circumstances and dynamic allocation of limited resources in operational context of a production strategy implementation. The effectiveness of management strategies for governing agroecological systems depends on a thorough understanding and intelligible representation of management strategies and farmers' decision-making behavior (Öhlmer et al., 1998; Edwards-Jones, 2006; Feola & Binder, 2010; McCown, 2012). The modeling framework discussed in this chapter must represent the biophysical system as perceived and understood by farmers, the elements of decision-making that underlie the management process, and the required resources that can be used or consumed. The decision-making models built within this framework are only abstractions; they cannot replicate all aspects of human knowledge or reasoning. However, they should make it possible to assess the physical feasibility and risk of intended plans realistically. The model of a specific farm (real or imagined) should help groups explore the planning of new agroecological management strategies in the face of knowledge gaps about the results of these strategies (especially highly innovative ones) and uncertainties about uncontrollable factors (e.g., weather, market, regulations). Learning in this process of adaptive management occurs through the informative practice of management itself, with the current management strategy being altered as understanding improves. In other words, the present approach is driven by knowledge-management objectives to develop a consistent set of processes to represent, organize, and disseminate agroecological knowledge. It uses dynamic simulation models and relies on a knowledge-creating and knowledge-sharing culture embodied in participatory-design approaches (Sautier et al., 2017). The growth of practical knowledge depends largely on accumulating and organizing information produced by experimental research. We recommend using virtual experiments (e.g., computer simulation) with an "integrated approach," in which progress is made by combining existing generic and site-specific knowledge from multiple domains (e.g., agronomy, ecology, farm-management science). Exploring and disseminating agroecological principles and achievements require uncovering and sharing knowledge among actors in a specific context. Knowledge expressed in the context of problem solving must be explicit for subsequent expansion and use. Some of this knowledge is tacit, which is generally difficult to articulate. Tacit knowledge must be converted into explicit knowledge (e.g., document or model) before it can be discussed, improved, and ultimately used.

This chapter is a preliminary attempt to develop guidelines for eliciting and modeling farmers' knowledge about management of their agroecological systems, which is necessary to test and disseminate the knowledge. Practical, empirical, and tacit knowledge in a partially known domain is best leveraged through social interactions, which justifies our focus on designing management practices through collective efforts in simulation-based participatory workshops.

2. Agroecological farm management

A production system such as a farm requires strategic and operational management. Strategic management consists of setting the overall direction of the system: choosing the type of production and configuring the overall long-term course. In comparison, operational management (Martin-Clouaire, 20187) consists of (i) committing to a plan of action to obtain desired and feasible results, (ii) making contextual changes to the management strategy (especially contingency plans) to keep the system moving in the chosen direction, and (iii) performing short-term actions that comply with the plan and circumstances. By committing to a plan, the farmer can pursue long-term goals and articulate its actions with intermediate sub-goals. Management behavior is also influenced by events that trigger adaptation of the plan when unexpected situations occur.

Farming systems require operational management that conforms to business objectives (e.g. maintain mid-term economic viability, satisfy contracts). Agroecology emphasizes sustainable production strongly by exploiting ecosystem services, maintaining long-term production, making farm work healthier and enjoyable, and contributing to improvement of environmental issues. Sustainable agriculture is more than a set of practices; it requires skillful management that promotes potential beneficial ecological processes while exploiting synergies between them and finding trade-offs when necessary. Farmers' management behaviors must be designed for the purpose and local context of the farm, and be adaptable to changing conditions.

There are as many farming systems as there are land-based configurations and types and combinations of management practices. When deciding to implement a farming system, farmers consider interactions among system components and the many spatial and temporal characteristics of possible actions. For instance, establishing a particular crop rotation may change the amounts and types of nutrients to apply and the appropriate pest management. No-till farming generally reduces soil loss and conserves soil moisture, but may also change weed management. Irrigation generally increases yields but also the amounts of nutrients that need to be applied. Management decisions that span seasons (e.g. crop rotations) interact dynamically with weather events and determine production constraints (e.g. soil moisture, pest populations).

Cropping practices can be divided into categories of agricultural activities that farmers perform to produce food, fiber, or energy. Major activities (Wezel, 2017) include:

- Soil and crop management: determining which varieties, crops, and crop mixtures to grow; their spatial distribution and temporal rotation; and the type of soil tillage (if any), cultivation, and conservation to perform to increase soil quality (e.g. reduce compaction, reduce erosion and increase organic matter) and conserve soil moisture.
- Pest management: determining weed, insect, disease, and other threats to crop growth and quality, and preventive actions (e.g. crop spacing, intercropping) or remedial actions (e.g. natural pesticides, biological pest control, planting directly in a cover crop or crop residues, trap cropping) to perform.
- Nutrient management: determining the additional nutrients the soil needs for crop growth and the kind and number of applications (e.g. manure, compost) required to improve soil biological activity, increase crop yields, and reduce the risk of contaminating ground and surface water.
- Water management: determining the amount of water required for crop growth and applying it efficiently (scheduling irrigation) given limitations on water availability, using practices such as a cover crop and mulch to reduce evaporation and decrease soil compaction.

When agroecological principles are applied in a suitable management strategy, several ecological functions (e.g. biodiversity conservation, soil and water conservation, biological pest control) can be generated and used, and yield can be increased and stabilized (Wezel, 2017). Helping farmers orient the complex dynamics of the processes involved means helping them develop the logic required to make rational management decisions, which result from combining their understanding of biophysical functioning with the effects of actions that are expected given farm characteristics.

Developing a farm-management model

Exploring the behavior of a new system first involves modeling and simulating the entire existing farming system and then modeling and simulating changes to it. To be relevant to farming-system design, research requires better understanding of the internal human representation of management practices (i.e., the management strategy and its resulting actions in the farm's context). A farming system's management strategy is embodied in how a farmer organizes, coordinates, and prioritizes production activities in time and how these activities are adapted as production progresses. We assume that a farmer willing to engage in agroecological transition follows goal-oriented management behavior, which raises several issues: identifying the goals, understanding how goals and actions are articulated in plans, and deciding on final trade-offs in order to initiate actions from the plan. Thus, a major focus is determining the role and pattern of mental models that farmers use to make judgments about pursuing, interrupting, or abandoning intended activities and scheduling executable actions depending on the current situation. Farmers' decision-making behavior, which is based strongly on their management strategies, involves physical and observation activities in the biophysical system, and interactions with the external context (e.g. weather, market, regulations). Most decisions depend on the circumstances but remain consistent with a pre-existing management strategy.

Developing a farm-management model requires eliciting and collecting details about many activities, goals, and available resources:

Assess the world surrounding the farm (market opportunities and limitations, funding availability, potential to collaborate with peers, availability of information and technical support, threat from regulations).

Assess the resources available, such as physical features of the land (e.g. field size, soil properties, layout, topography, livestock production), machinery, equipment, and amount of labor (farmer, family, employees) available during the year.

Define the farm's mission and goals.

Describe the "primitive" activities (the most basic unit of activity (i.e. not broken down further)) that describe all possible actions by the farmer, including observation activities (e.g. of pest populations).

Examine dependencies between activities (e.g. demand for the same resource; timing, sequencing and synchronization requirements) and develop a plan of action that can achieve the farm's goals by aggregating the primitive activities (using temporal and procedural operators) applied to spatial entities and the required resources.

Establish preferences and priorities to use when selecting activities for immediate execution and allocating resources among competing activities.

Identify events that can trigger revision of goals and the plan and incorporate the corresponding adjustment into the previous plan.

In particular, the model designer must identify nominal management behavior (i.e., how activities and resources are coordinated under ideal circumstances). It can be modeled (Martin-Clouaire and Rellier, 2009) as a collection of primitive activities that are organized in a plan involving different actors and tools. Activities in the plan can be scheduled to occur simultaneously or sequentially, only during certain temporal windows, or with a risk of conflict (e.g. multitasking) or constraints (e.g. infeasible to perform) that must be resolved eventually. Once the nominal behavior is determined, the model designer should consider what could go wrong and then introduce flexibility (Martin-Clouaire and Rellier, 2011) into the plan by making optional the activities that are not mandatory, by creating one or more branching points, or by enabling changes to the plan in response to events. Since resources are often limited and may be unavailable when needed, deadlines may not be met, especially if the context has changed in an unexpected manner or an external event makes the plan obsolete. In these cases, other management activities may be required beyond the nominal behavior.

4. Decision-relevant concepts

4.1 Activities, Operations, and Resources

Activities are the most important construct in our conceptual model of farm-management behavior (Martin-Clouaire and Rellier, 2009, Martin et al., 2011, Martin-Clouaire et al., 2016). There are two different activity types: primitive and composite. Each primitive activity represents an action to be performed (e.g. grass cutting) to an entity (e.g. a field) by one or more actors. In other words, it denotes a technical operation (something to be done) to be applied to a particular biophysical object or location (if feasibility conditions are satisfied) by executing agents and possibly other resources (e.g. machinery, inputs). A primitive activity has local opening and closing conditions, which are defined by temporal windows and/or predicates (Boolean functions) that refer to biophysical states or indicators. The incremental change to the biophysical system as the operation is performed is a functional attribute of the operation. Operations can be instantaneous or occur over time, in which case they are executed at a context-dependent speed and might be interrupted. A primitive activity can be viewed as an abstract description of an action. Questions to ask about a primitive activity include the following:

- What operation must be performed?
- Where will it be performed?
- How early or in what situation can it be performed?
- When must it be completed?
- How will it be performed?
- How much time, energy, and resources will be required to perform it?

The ability to benefit from organizational and timing flexibility depends on effective execution, which is determined by the resources involved (e.g. operation resources, actors). Representing the resources (Martin-Clouaire and Rellier, 2011) and their availability carefully is essential to understand the situation and the potential for improvement. In short, a resource is an entity that supports or enables the execution of activities. Typically, resources include those who perform activities, required machinery and facilities, and inputs (e.g. seeds, fertilizer, water, fuel, funding). Resources are, by definition, finite and have a strong influence on when and how activities can be performed. A resource's availability is restricted by constraints that specify conditions under which it can be used or consumed. Constraints are temporal (statically or dynamically determined temporal windows of availability), capacity-related (the amount available), or state-related. Temporal constraints on the availability of actors may be flexible; for instance, working time per day can vary slightly if needed, but total working time per year must comply with strict laws.

Observation activities differ in that they do not change the biophysical system directly; nonetheless, they play an essential role in agroecology. Technology for sustainable farming must emphasize measurement and observation equipment or services (e.g. soil analysis, manure analysis, pest identification) that help farmers assess their situations. It also must focus on larger system scales. The predators and parasitoids that control pests often require habitats larger than those found on small farms. They require instruments and indicators that illustrate ecological states and relationships on and among farms at the landscape scale.

4.2 Goals and plans

An important principle of most decision-making processes is that the motives for performing management behaviors range from explicit to implicit. A variety of values and goals motivate farmers' actions. Values are more permanent characteristics of farmers, such as traits they want to embody (e.g. integrity, safety, recognition, sustainability). Some goals simply promote these values, while others relate directly to the farmer's production vision or purpose of the farm. Some goals are ends in themselves (e.g. increase free time, improve soil fertility), while others are only means to an end (e.g. introduce a legume cover crop). The goals specify milestones and end points toward or away from which relevant actions should lead. Examples include (i) state-based goals such as reducing vulnerability to pests, reducing carbon emissions, maintaining soil health, increasing input efficiency, reducing weed pressure, and avoiding severe water stress and (ii) more abstract goals such as achieving economic viability of the farm, obtaining social approval, maintaining a stable income, increasing the standard of living, creating good conditions in which to pass the farm to the next generation, and maintaining or improving environmental quality. The following list of goal-related questions helps model designers analyze a goal thoroughly:

- What are the reasons for pursuing this goal, and why do these reasons matter?
- What specific results are intended?
- What benefits are expected from achieving this goal, and what are potential consequences or costs of not doing so?
- How can achievement of this goal be determined?
- How does this goal align with, support, or advance the farmer's overall mission, values, and principles?
- When will the goal be achieved? Do milestones need to be met along the way?
- What obstacles could arise while pursuing this goal? What can be done now to prevent them or address them if they do arise?

Goals, once carefully considered, require a response by the farmer in terms of intention to do. Thus, in a planning process, the farmer's goals must be converted into a plan that will achieve them. Decisions regarding the strategic direction of the farm need to be cascaded into operational decisions in a plan that describes what actions are required or suitable and how to coordinate them on the farm in the context in which they will be performed. A plan specifies how to achieve, over time, a series of connected goals in which the achievement of each satisfies an immediate need and provides a stepping stone to a more ultimate goal. Identifying an action that is useful for achieving a goal is not always simple because several actions may be necessary and certain actions may conflict with other goals (e.g. short-term profitability vs. long-term viability). Little is known about the cognitive process that farmers use to relate desired situations to a consistent plan of action. Individual farmers' goals and the goals' perceived relationship with plans are hidden within conscious and unconscious cognitions and emotions. Farmers use some kind of library of recipes rather than plan from first principles. Thus, we do not attempt to model this planning process, especially because (i) agroecology remains far from a normalized procedure, which would have made it possible to identify elements of the mental model necessary for planning, and (ii) collective design is more complex than design by an individual. Instead, we focus on making characteristics of management behavior (especially goals and plans) explicit to make them objects that can be examined, discussed, and communicated.

Certain characteristics of a goal are useful when developing a consistent and feasible plan of action, such as importance (i.e. attractiveness, relevance, priority), difficulty of achievement, temporal range (i.e. proximal or distal), and specificity (i.e. abstract or concrete). The goals also provide temporally bound and measurable results to be achieved. The timescale may be the seasonal horizon of crop production, or longer.

Activities can be further constrained by expressing temporal relationships among them and the potential for iteration, logic associations, and relaxation. Composite activities can be constructed using programming constructs (e.g. *before*, *co-start*, *iterate*, *or*, *and*, *optional)* that specify temporal sequence, iteration, alternatives, aggregation, and optional execution of activities (primitive or composite). These constructs connect all activities except the overall plan, which has no higher-level activity. Committing to a plan transforms it into an intention that flexibly describes the when, where, and how of what is appropriate to achieve the corresponding goals. With this flexibility, plans play a directional role, providing general guidelines, focus, and flexibility in execution. As an ongoing process, plans can also be adjusted in reaction to events. Plans can change, but nonetheless persist once farmers commit to them; they change only when important events occur and when conditions warrant. Farmers' actions are governed by a continuous process of pursuing the goal and adapting it to the changing environment and its contextual constraints. When farmers engage in joint activities, their actions are also governed by the actions and intentions of the other co-actors.

Temporal specifications in plans reveal much about the timing of decisions and actions. Most intra-seasonal decisions correspond to stages of crop growth (e.g. land preparation, sowing, harvest) and intermediate operations (e.g. fertilization, pest management, irrigation). However, the timing of decisions and actions are also determined strongly by events, such as completion of an activity or a weather-related event. Often, several sub-plans (conjunction of composite activities) are used to express similar interventions to be performed on different spatial entities (e.g. fields, rows). The order in which these entities are treated may also need to be specified through priorities.

4.3 Preferences and priorities

Preferences are personal criteria that help to differentiate what is useful, good, beneficial, or important. Preferences influence the choices that individuals make and are a key characteristic of farmers' management behavior. Practical reasoning involves deciding what to do or justifying what one has done. Farmers can influence how the world changes and have preferences for the resulting states. Since their ability to act is limited, they may need to choose among several beneficial actions that, from their viewpoint, would improve the state. Their preferences are essential discriminating criteria. Actions have expected effects but can also have negative consequences; thus, preference-based decision making is required to decide whether an action's potential trade-offs are acceptable or whether other actions have better trade-offs. Conscious preferences or priorities must be expressed. They are also necessary when choosing the resources to allocate to primitive activities, which restrict which primitive activities can be executed. Doing one thing means that other things cannot be done.

More generally, preferences and priorities convey internal criteria for evaluating alternative goals and primitive activities and for allocating resources. They help to choose among alternatives and resolve conflicts. They are also used to make decisions in response to different kinds of pressure (e.g. finishing an activity, achieving a state, or freeing up resources by a given date), opportunistic or personal attitude (e.g. continuity and harmonization of activities, cost/benefit considerations), and commitment to the future.

In decision making, preferences are informally connected to values (i.e. aspirational traits). In action-determination situations, motivational attributes are used to make certain alternatives more preferable or less preferable than others. Prevention (i.e. avoidance) goals may involve sensitivity to loss when punishment is feared, while target goals may involve sensitivity to gain. This attitude must be expressed through preferences and priorities.

4.4 Events and reactions

Due to uncontrollable factors (especially weather and pest infestations), farmers cannot rely on routine, calendar-based activities. Their actions must be based on observation and prediction. A plan may encounter certain events (e.g. a long drought) that lie outside its bounds. Specifying changes to a nominal plan as a function of circumstances is called "conditional adjustment". Identifying alternative actions that can be performed if the original plan is inadequate due to changing circumstances is crucial for a robust management strategy. Anticipating a suitable change when things do not go as expected is a cautious and safe attitude.

The element that triggers conditional adjustment is either a calendar condition that becomes true on a specific date, or a state-related condition that becomes true when circumstances meet the condition. The adjustment can be any change to the current plan, such as removing or adding activities, or changing the resources used in certain activities. In this way, management can respond rapidly to address unexpected (but still possible) fluctuations in the external environment and other contingencies. Not all (and usually few) elements of a plan need to be stated in full detail; some can emerge spontaneously through conditional adjustment, and interactions between the situations and constraints that are considered each time decisions are made about which actions to perform.

5. Example of an agroecological management strategy

As an example, consider a virtual farm in the agrarian region west of Toulouse, France. From personal experience, the farmer is aware of consequences of conventional agriculture on the environment and food system, as well as of changes in societal demand. The farmer has also experienced increasing threats to cash-crop income due to an overall decrease in productivity and climate change. The farmer begins redesigning the farming system by deeply reconsidering its production and management and breaking them down into goals. This reflection prompts the farmer to look into the potential of organic agriculture. Being relatively unfamiliar with it, the farmer adopts a cautious approach to address production risks and decides to convert only one section of the farm, with the initial agronomic objective of improving soil fertility to ensure acceptable yields over long periods without agrochemical inputs. Each field of both the conventional and organic sections then requires an annual or multi-year cropping plan. The planning process is knowledge-intensive and especially challenging for the organic section, which requires new combinations of agroecological practices, techniques, and equipment. For simplicity, the sample plan includes only sowing, weeding, and harvest (Fig. 1), thus excluding storage, distribution, and observation activities (e.g. for weeds, insects, and diseases).

```
And(
    Before(
          Sowing-alfalfa,
          Iterate (
                Before (
                      Optional (Mechanical-weeding-alfalfa),
                      Harvest-alfalfa)),
          Iterate (
                Before (
                      Direct-drilling-wheat-into-alfalfa,
                      Harvest-wheat))
          ),                                              Field1
    .
    .
    .
    )
```

Figure 1. Simplified three-year plan for one field. Dots indicate placeholders for other fields.

The plan is based on combining the nominal sequence of activities on each field. For example, the sequence for field1 starts with alfalfa sowing (Fig. 1). Repeatedly alfalfa is then mechanically weeded, if necessary, and then harvested. The plan continues with the iteration of direct drilling of high-stalk wheat into the alfalfa for two consecutive years. Primitive activities occur during temporal windows and require resources (Table 1), while iteration activities have specifications (Table 2).

Table 1. Sample temporal windows and material resources involved in primitive activities

Primitive activity	Temporal window	Resources required

Sowing-alfalfa	[15 Sep-30 Sep]	rotary harrow, alfalfa seed drill, roller
Mechanical-weeding-alfalfa	[1 Mar-15 Mar]	weeding harrow
Harvest-alfalfa		mower, drying system, and labor provided by an external company
Direct-drilling-wheat-into-alfalfa	[1 Oct-20 Oct]	rotary harrow, wheat seed drill, roller
Harvest-wheat	[1 Jul-10 Jul]	combine

Table 2. Sample characteristics of the two iteration activities

Iteration	Specifications
Alfalfa harvest	First harvest: at bud stage Subsequent harvest: at flowering stage
Wheat sequence	Two times

The plan of activities, which is developed or reconsidered once per year, is necessarily tentative. It may need to be changed due to overly wet critical periods, unforeseen lack of availability of required equipment or labor, pest-related events, or important contingencies. Thus, the future behavior described by the plan is accompanied by adjustment rules for making last-minute changes. For instance, if the soil is too wet or too dry in October, alfalfa sowing will need be postponed to [15 Mar-15Apr]. More generally, if the crop fails to establish, it can be abandoned, replanted, or replaced with a cover crop or another cash crop. The adjustment may also influence the dates or conditions of an activity and even the priorities ultimately invoked to determine which actions of the plan to select and perform in the current situation. For instance, in a dry year, priorities among crops and thus among activities may change because some crops carry more risk than others.

The basic concept is to rely on ecosystem services and preventive measures in nature to maintain or improve fertility and regulate pests and diseases in crops. The main issue is to determine the practical actions that can maintain or enhance these ecosystem services to correspond to the farm's current situation. Reduced tillage, intensive use of cover crops, intercropping, living mulches, and rotations containing crops with large amounts of post-harvest residue are options that need to be tested for each field to assess their effectiveness and feasibility at the farm scale under a variety of weather scenarios. Thus, for each field of the organic section, the farmer should first determine what types of economic-oriented crops, green-manure crops, and cover crops should be planted; when and how they should be planted; and when they should be harvested, killed, or incorporated into the soil. The farmer has a few cash crops that can generate high income. Crops are first determined for fields based on market, agronomic, and logistical considerations. Key crops are assigned to the most suitable fields as long as they do not compromise the fields' soil quality and long-term productivity. The logistics of labor- and equipment-intensive activities (e.g. sowing, harvesting) must be considered when developing an annual plan. In addition to meeting the current year's production goals, the farmer designs crop sequences to prepare for future key crops.

6. Discussion and conclusion

The modeling framework outlined in this article enables farmers to describe their operational decision-making practices that determine crop-production management at the farm scale clearly and non-ambiguously. It also considers characteristics of the farm's land as well as the labor and material required. Farmers need be encouraged to experiment, improve, share, and spread their own perception and knowledge of farm-production processes and how to influence them. The modeling provides important benefits, including the increased range and complexity of management behaviors that can be examined, the additional insights that can be gained for a given management strategy, and a greater ability for expert-based model validation. Explicit representation helps to reveal broad gaps in current understanding that would be overlooked easily in solely verbal assessments.

The cognitive architecture presented can be supplemented with biophysical process models and embedded in a computing environment that simulates event-based dynamics (Martin et al., 2011). Using these farm-production models in simulation experiments can help in understanding complexities of interactions of the processes involved. Simulation provides a basis for experiential learning in realistic farming environments. The models can incorporate farmers' estimates for uncertain or incomplete data and farmers' opinions about difficult-to-measure parameters based on personal knowledge and experience. Most studies focus on only one or a few elements of a specific farming system and thus fail to consider trade-offs and conflicts between interacting components. Only a simulation model that represents the entire range of factors that influence farm households can address the behavior and performance of a farm as a whole and how it could evolve if uncontrollable factors change unexpectedly.

A simulation model can help screen out management options that would be inapplicable in the farm context or unacceptably risky given uncertainty about the response to certain actions. Simulation can reduce uncertainty and reveal relationships within the agroecosystem and between the biophysical context and human actions. Simulating the management strategies presented in this article can help assess the suitability of their timing, the pertinence of observation activities, and the ability of resource availability to meet demand. Simulation can easily identify a management strategy that relies on overly tight deadlines or overly small temporal windows or that demands too much labor during certain periods. Seasonality tends to place high premiums on timely performance of critical agricultural tasks (e.g. sowing, harvesting). Although the available labor pool may seem large enough to provide the required amount of labor during the year for all crops, significant labor bottlenecks may occur when tasks must be performed quickly at specific times. Labor is frequently the limiting factor, but other resources (e.g. fertilizer, seeds, irrigation water) must also be available at specific times. Simulation is also essential to test the robustness of management strategies in the face of uncertainty in external factors, especially climate change. Since weather is uncertain, farmers choose varieties, crops, or crop mixtures that tolerate weather variations better; these options can be explored deeply. Equally important, simulation helps determine appropriate reactions to weather variations by changing the plan to sow or harvest a second crop in an extremely dry season. Such conditional adjustments require a mental model of context-dependent possibilities in the future.

Efforts to develop effective tools to facilitate participatory elaboration of goal- and plan-based decision-making strategies are increasing as an important step to facilitate cooperation, mutual understanding, and capacity for generating innovative situation-specific solutions (Sautier et al., 2017). In the context of agroecology, which lacks a universal model that can consider variations identified in practice, it is important to use all knowledge and experience available to build an empirical understanding of what can or must not be done, depending on the context. To this end, farm models play an essential role in focusing discussion and reasoning when used in participatory workshops involving 3-5 farmers and 1-2 facilitators. Dialogue is a central element in developing critical thinking and challenging norms and assumptions. The entry point of a workshop is often the farm of one of the participants used as a case study that the group examines by developing and testing ways to transition to an agroecological system. The process involves collective problem solving, with the basic philosophy of learning primarily from each other in the group rather than being taught from the outside. Farmers can increase their understanding by combining existing knowledge from different domains (e.g. agronomy, entomology, ecology, management) and different perspectives of the workshop participants.

Thus, modeling supports collective experiential learning in complex, realistic farming environments. It contributes to collaborative development of new management strategies due to well-focused peer-to-peer discussions supported by agronomic, environmental, and economic results of simulation experiments. Models are helpful in simulation experiments that map inputs from a specific case study onto outputs that can reveal essential and understandable insights about the resulting system behavior. The model must facilitate exploration of diverse cases and support collective development of sound argumentation that sheds light on the design problem and enables new ideas to emerge. Groups can often be more intelligent than individuals, combining information from a variety of sources, and overcoming individuals' biases, errors, and limitations. Modeling and simulation foster the diversity of cognitive skills in the group and improve participants' ability to understand the situation, learn, and adapt.

There is extensive recognition of the importance of participatory processes to collecting available knowledge, making it explicit, establishing common understanding of system dynamics, and finding agroecological solutions through innovative management actions. This participatory process combines farmer knowledge and experience with scientific knowledge of ecological dynamics and constraints, which can help participants build a shared view of causal relationships that explain the nature of ecosystem-service tradeoffs. Capturing differences in knowledge and understanding of biophysical functioning of agroecosystems is a critical advantage of our modeling approach, which combines the potential to represent and communicate management strategies, making it possible to analyze them critically, with arguments for how to improve them. Salient aspects of the target agroecological system can be inspected, criticized, and modified in its corresponding model until the model agrees with the mental models shared by workshop participants. For a framework to function well as an evaluation tool in a participatory context, it must provide a valid and useful representation of system dynamics and be simple enough for non-specialists from different backgrounds to understand and use. This framework provides a powerful way to use both empirical data and farmers' experience to build a mental model collectively to identify important information gaps and develop tentative solutions. Although hypothetical and superficially realistic, a model can organize knowledge in a consistent manner and provide inexpensive and reliable trial-and-error learning. For the model in the approach presented, validation consists of identifying consistency, or rather lack of inconsistency, from the viewpoint and aim of workshop participants.

This modeling approach has some limitations. As mentioned, it cannot replicate innate human knowledge-management skills such as planning. Information management is another essential skill that the model represents superficially. We did not attempt to model automatic learning from experience (i.e. the information that should be stored, how can it be summarized by decision-relevant indicators), although it would be useful in a new domain such as agroecology. In addition, it does not address farm management at the scale of multiple farms, which raises issues of shared goals and collaborative decision-making involving several farmers. While individuals' farm-management decisions are critical to their business, their decisions about coordination with other farmers (e.g. whether to coordinate, with whom, and how) are equally important in agroecology. Although farm-scale coordination decisions are motivated by individual farmers' objectives of increasing profit and/or decreasing risk, they can have far-reaching and complex implications for the overall provision of ecosystem services. This in turn affects the results and long-term sustainability of the farmers' agroecosystems. To accomplish common goals that cannot be achieved by an individual farmer, two or more actors must coordinate their plans and actions.

The inherent strengths and weaknesses of the farm-management models addressed in this article have crucial implications for application to agroecological farming-system design. Their recommended use in participatory workshops emphasizes their primary function of supporting elicitation of farmers' agroecological and production-management knowledge. This use promotes dialogue among participants when building a model of a specific farm, analyzing simulation results, and revising the model. The dialogue during modeling results in shared understanding based on clarifying assumptions and implicit beliefs of the participants' mental models. The discussion after a simulation experiment focuses on collective verification of the consistency of the results and generates intuition for improving aspects of the simulated farm, including the management strategy. Agroecology requires a shift in the way we generate, learn from, and act on evidence. The use of virtual worlds and simulations to enhance the evidence extracted from real-world experiments is clearly promising, although more research is needed for large-scale application of the approach.

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