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Ontological Foundation of Ecosystem Services and the Human Dimension of Agroecosystems

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Abstract

The purpose of this contribution is to lay down a preparatory groundwork for an ontology of ecosystem services in the setting of agroecosystems viewed as social-ecological systems. This ontology aims at defining a set of representational primitives with which to model agroecosystems, through the prism of ecosystem service flows to and from agriculture. It helps delineate between biophysical structures, processes, functions, and ecosystem services. On the human side of agroecosystems, the ontology includes a conceptualization of the behaviors that govern the management of ecosystem services at different levels. It strengthens the existing analytic basis of multidisciplinary research on ecosystem services in agroecosystems by prompting modelers to stick to a homogeneous dynamic-system decomposition of the target agroecosystem. Most importantly, it provides the conceptual link between biophysical research on ecosystem services and equally important considerations on cognitive and social aspects involved in agricultural and landscape-level decisions that aim at implementing agroecological principles.

Keywords

Ontology, Ecosystem Service, Social-Ecological System, Agroecology, Decision Making

1. Introduction

Agriculture is both critical for human well-being and a major driver of environmental decline [1]. Addressing the performance and resilience of agroecosystems will require research and development to promote and support a shift from current agriculture to agroecological practices that are less dependent on synthetic chemical inputs and generate ecologically-balanced and economically-viable production over long periods of time. To handle this issue we need an integrated approach that links different world views, and bridges different spheres of knowledge. The concept of ecosystem services (ES), popularized by the Millennium Ecosystem Assessment [2], provides the seminal idea for such an approach that connects human interests with natural environment. Unfortunately, no uncontroversial and universally accepted definition of an "ecosystem service" has yet emerged [3]. This is probably inherent to the integrative nature of the concept, the intricacies of aspects to consider, and the diversity of contributing scientific disciplines and interested parties. This paper sticks to the core idea of ES as the contribution of ecosystem structures and functions—in combination with other inputs—to human well-being [4]. ES result from the interactions between plants, animals and microbes, as well as biotic, abiotic and human-engineered contributions. In the case of agroecosystems, the ES are heavily dependent on uncontrolled inputs such as rain water and solar energy. They are also strongly influenced, purposefully or not, by agricultural activities of farmers that introduce inputs and make important transformations through their production practices.

Agroecosystem management based on ecosystem services is a major challenge for rural areas now and in the future. For instance, caring about biodiversity in soil, pollinator habitats on farms, and restored ecosystems surrounding farms can help build sustainable productivity on farms by enabling or increasing the robustness and synergetic effects of some essential ecosystem services. Healthy on-farm ecosystems can also play a role in providing services outside of agriculture, such as wildlife habitat and groundwater quality. Adopting, discovering or implementing service-centred agroecological principles requires fundamentally different ways of designing, monitoring and managing agroecosystems because a wide range of partially known ecological processes, several spatiotemporal scales, and human cognition together with various social drivers are playing essential roles. The concept of ES can act as a facilitating tool that improves communication between interest groups and academic disciplines (ecology, agronomy, sociology, economics and modeling sciences), and helps decision-makers (farmers and policy makers in particular) in shifting from current agriculture to service-based agroecology. Effective ecosystem-service-based interventions depend on a clear understanding of the interactions between biological, physical, and socioeconomic aspects of the services [5]. Making decisions about how to efficiently generate and combine ecosystem services is difficult because the consequences of different actions may be uncertain and hard to quantify, both economically and environmentally. Monitoring/assessing the effects of actions and building judgment before action necessitate cognitive skills and endeavor to acquire knowledge and understanding through experience and interactions between stakeholders. The connection of ES with human agents (individuals, groups, institutions) and the affiliated processes (e.g. production management, action coordination, communication, negotiation, policy making) needs to be examined from a scientific perspective that favors identification of strengths and weaknesses of the current practices, and opportunities to improve them.

Although undisputed definitions of many notions linked to ecosystem services are not yet attained, much foundational material has been used and published in scientific or policy-oriented documents. Since different perspectives exist, confusion and inconsistencies predominate across disciplines and agents involved in this relatively new domain. A shared conceptualization would greatly contribute to establishing common accounting and reporting systems, and in formulating common questions, criteria and methods [6] as seen in other domains. Indeed, there has been a growing interest in the application of ontology-based conceptual modelling principles for providing well-founded semantics and methodological guidelines to be used in the medical domain [7]. The Gene ontology (http://www.geneontology.org) is another example of a successful ontology. It has been used to standardize the representation of genes across species and databases, and provides a controlled vocabulary. In ecology, the approach has been used in the OBOE project [8] to capture the semantics of generic scientific observation and measurement in the domain. ENVO [9] provides an ontology for specifying a wide range of environments relevant to multiple life science disciplines. Another use of ontologies, which is the one adopted in this work, is as a knowledge engineering tool that facilitates the development, evaluation, exploitation and communication of models of complex systems [10] [11] and capitalization of knowledge about these systems.

The purpose of this paper is to lay the groundwork which, we hope, will in due course form the basis for an ontology of ecosystem services and affiliated concepts in the setting of agroecosystems viewed as social-ecological systems. This ontology aims at defining a set of representational primitives with which to model agroecosystems through the prism of ecosystem service flows to and from agriculture. The ontological framework also includes a conceptualization of the behaviors that govern the management and use of ecosystem services at different levels, ranging from individual farmers to community groups and institutions. It provides the conceptual link between biophysical research on ecosystem services and equally important considerations on cognitive and social aspects involved in agricultural and landscape-level decisions that aim at implementing agroecological principles. Given the goal of the enterprise, the presentation is largely discursive rather than formal.

2. Ontological Foundation

Ontologies [12] [13] are formal frameworks that apply fundamental principles and formalisms, drawing on mathematical logic to represent categories conceived or perceived by observations of reality. The major role of ontologies is to provide a well-defined set of objects to structure domain-specific theories. The goal is to provide a systematic way to model a domain of interest for the purposes of communicating about it, studying it or tackling difficult problems in it.

A domain ontology defines (or specifies) the concepts, relationships, and other distinctions that are relevant for modeling in the domain. The specification of an ontology takes the form of definitions of a representational vocabulary (classes, relations, and so forth) that provide meanings for the terms and formal constraints on their coherent use. A concept has to be understood as the meaning of something conceived or perceived by scientists as universal in the domain and defined by a unique combination of characteristics. In this sense, a concept is an abstraction.

We use the term "category" for everything that is deemed necessary to structure a theory explaining or accounting for the natural and/or social phenomena of interest. Some of this material is very general and basic; for this reason it is often referred to as foundational or top-level ontology. Several such ontologies (e.g. BFO [14], DOLCE [15] and GFO [16]) have been built, but none have gained widespread acceptance as a de facto standard. The differences often stem from philosophical and theoretical arguments, but are sometimes merely the result of personal preferences with no method to objectively compare them. Consequently, the domain-specific ontology that we propose here, relies on a simple top-level ontology that was derived from these sources and the research literature about dynamic systems and discrete-event system simulation [10] [17] [18].

Categories are described by terms in a natural or formal language. It is convenient to treat each category as a class or frame [19], that is, a configuration of elements that share some traits. Classes can be organized in a generalization/specialization hierarchy, which enables linking a class to another class that is either more specific (subclass or subcategory) or less specific (superclass or supercategory). For instance, the category "pest control services" is a subclass of the category "regulating ecosystem services", which in turn is a subclass of "ecosystem services". The categories are described through their properties (also called "attributes", "qualities", "features", "characteristics" or "types") that can take simple values (e.g. a number for a size property, or a string for a name property) or point to other categories (e.g. the parts composing a category). For instance, the description of the category "meadow" might involve the properties: name, size, location, and boundary entities. At construction time a category inherits the properties from its parent category (supercategory) and is specialized through, for instance, extra properties or the introduction of new restrictions on the values that the properties are allowed to take. Such restriction for a given property is called a facet. Facets can be used to specify what is known about a particular property of a category, such as the unit in which the size of a field is to be expressed, the range of possible values for a numerical property, the cardinality of a multivalued property or the class that the value must be an instance of. A category is a generic description of a concept (a data type). A concrete realization of a concept (e.g. the field just behind the barn) is called an instance of the concept. The relation that holds between an instance and a class (a category) is akin to set membership.

Three essential types of categories are recognized: entity, event and process. They are not exactly the same in the three top-level ontologies and are not classified in the same way. What we call an entity (also called a continuant in BFO and GFO, and an endurant in DOLCE) is something existing at an instant in time, having some properties (e.g. spatial descriptor of size or shape, location, connectivity, part hood or composition) which are subject to change. An entity has a lifetime, *i.e.* has birth and, possibly, death. Material entities (e.g. a person, a forest, or an animal community) are types of entities which inhabit a spatial region. Examples of immaterial entities include a decision, law, service or spatial region. The state of a subpart of the world at an instant in time is simply a snapshot of the current constituent entities together with the current values of their properties. An episode is a time-bounded history of the system (or part of) consisting of a sequence of consecutive states (*i.e.* an historical record of the changes endured by the system).

The terms "process" (called a perdurant or an occurrent in some top-level ontologies) and "event" (also called an occurrent) are understood slightly differently in the various top-level ontologies. Some consider process as a subcategory of event. Others [20] treat them as distinct categories, which is the approach we adopt here. We define an event as a particular time where something important happens (*i.e.* that is potentially followed by abrupt and significant consequences). In other words, an event is something that takes place instantaneously within the environment of interest, and that potentially induces changes in addition to those that are already happening. Air temperature staying below a certain threshold for a certain period of time can be seen at the end of this period as an event that triggers a freezing process. Events can come from external sources (e.g. climatic events such as hail, pest outbreaks) or can be a realization (logical consequence) of a set of processes (including those governing the change of state of the entities). They can also be identified as a salient demarcated evolution in an episode of the life of an entity (e.g. the stage change of a crop). Some events are self-generated. For example, the event of arrival of sunlight on one day generates it for the next one. An event can also generate other events that are causally connected to it. For example, a river-overflow event can generate an erosion event and a change in soil-fertility event. The use of the word "event" here is just a restriction of its everyday meaning, which refers simply to a significant happening. Contrary to other top-level ontologies, we use the term to designate instantaneous happenings; happenings that have duration are dealt with using the notion of a process. A chronicle is another useful concept defined as a chronological record or register of events within a historical window.

A process is responsible for entity changes, including their creation, elimination and transformation, through the modification of property values. A process possesses a functional property, called a transition function, which defines how states change, *i.e.* the law or rule that governs changes on the basis of: 1) current and, more rarely, past states, and 2) inputs that are external to the entities to which the process applies. A process depends on: a) entities that are its bearers and b) events that can cause it to be activated, annihilated, suspended (deactivated), or reactivated. A process is realizing when an event activates it (initializing or instantiating event) and proceeds until an event triggers its suspension (the process still exists) or its definite annihilation (the process ceases then to exist). A suspended process may be reactivated by an event (a management activity may be suspended at the end of a day and resumed when the next starts). The natural end (completion) of a process (e.g. the filling of a container stops when the container is full) can be seen as an event, which itself will cause other processes to be activated. A process is not itself subject to change except for its status: inactive, active, suspended. Photosynthesis is an example of process which has a plant leaf as bearer and is initiated with the event of creation of the leaf and ends with the death of the leaf. The process is suspended when sunlight falls below a threshold and is reactivated as soon as sunlight comes back. Any process must have some material "host" which may be said to enact it—here "material" should be understood in a broad sense to include, for example, objects, energy and fields of force. Belief updating is a human process by which a human agent infers new facts from other just-obtained facts (e.g. just after a monitoring activity). Negotiation is an example of social process.

Any category can be made more specific by constructing a subcategory that has additional properties or additional restrictions on the possible values of one of the properties of the original category. For instance, the category "entity" has "material entity" and "immaterial entity" as subcategories. The category "material entity" can be further specialized into two subcategories: "matter" (itself further decomposed into water or clay for instance) and "objects" (e.g. plant, agent). The taxonomic relationship that links a category to a subcategory is commonly referred to as the "is_a" relation. To deal with a concrete situation the categories need to be instantiated. An instance of a category is a specific example. An ontology together with a set of such instances constitutes a knowledge base.

Dealing with ecosystem services requires reasoning about entities located in space, and such entities have spatial structure. Therefore, the ontology must provide the means to describe and reason about topological properties of individual regions and spatial relationships between them, such as: contact, connection, overlap, boundaries, interior, holes and the relationship of the part to the whole. The formal theory that supports the part of upper ontology dealing with space is known as mereotopology [21] [22].

3. Agroecosystems and Services

Relying on the above background material that defines the top-level concepts of "entity", "event" and "process" this section draws on them to set forth the meaning of more specific concepts commonly used in the ES domain, in particular "system", "function", "service" and "disservice", which are specializations of "entity" and refer to processes and therefore to events.

3.1. Systems

A system is an arrangement of components or parts that act as a coherent whole, usually attached to one or several processes that transform inputs into outputs. Clarifying the system boundary is an essential first step in any analysis. The positioning of the boundaries and the granularity (level of detail) of the system depend on the purpose of the observer or modeler interested in the system. The main properties include:

- organized composing entities (structure);
- processes;
- inputs;
- outputs;
- types of events that potentially affect it;
- types of events originating from the system and potentially affecting other systems.

The composing entities of system define its boundaries. What is in outside the system is called its environment. Inputs and events that can potentially affect the system constitute "external drivers". A common cause of confusion is failing to distinguish between external drivers and internal dynamics, the processes that respond to events and inputs. Feedback occurs when outputs of a system are routed back as inputs forming a circuit or loop. Feedbacks should stay within a system; this principle helps define the system boundaries.

Plants, farms or watersheds are all examples of systems in the domain of interest of this paper. For a farm, the components may include the farm's physical capital (e.g. plots, meadows, equipment, non-farmed areas such as wood, stream, pond or wild habitat), human capital (labor, knowledge, skills) and financial capital. Detailing these categories is beyond the scope of this paper.

An ecosystem is a system that includes interactive living entities and the abiotic environment at a specified location. Addressing questions about ecosystems requires dealing with notions such as biome, habitat and niche. A biome is an ecosystem which contains ecological communities adapted to the environmental conditions experienced at the site. A habitat is an ecosystem which can support the persistence of a given population. A niche is an ecosystem which is that part of a habitat which supports, or can support, a given biological species. For present purposes we shall not go much beyond this, although a fully articulated environmental ontology would clearly be of great help for modelers. ENVO [9] can be taken as a basis.

An agroecosystem, as the name implies, is essentially an ecosystem that hosts activities of agriculture. It is somewhat arbitrarily defined as a spatially and functionally coherent unit that is primarily dedicated to agricultural production. However, an agroecosystem is not restricted to the immediate site of agricultural activity (e.g. the farm), but rather includes the region (landscape or watershed) that is impacted by, and impacts on, this activity. It concerns the living (including humans) and non-living components involved in that unit, as well as their interactions. Besides ecology, agroecosystems have human and socio-economic dimensions that make them social-ecological systems (see the next section). Interactions between individual components at small scales give rise to the macro-scale properties of the system, which are often emergent features that are not predictable from the components and the description of their interactions.

3.2. Functions

A function is a well-identified natural phenomenon that is confined to a subsystem (e.g. root system of a plant) and is often named in relation to its main effects (e.g. absorption of water and nutrients in the substrate). In other words, it is defined as the end that a subsystem can bring about by virtue of its physical bearing structure and the realization of a process or processes including at least the processes that created or maintain the structure. Functions are traits of ecosystems that exist independently of human value judgments and actions. A function is what the structure does by enacting the processes that generates an expected output from input.

A function has a name and inherits properties from more general specifications in the class hierarchy, here the entity class (Figure 1). It has 5 key properties: bearer, input, output, process and enabling condition. The bearer points to a subsystem, *i.e.* a material host (a structure consisting of a part of the agroecosystem of interest) subject to changes. The input designates a set of sources of matter or energy required by the underlying processes. The output concerns a set of entities affected or controlled by these processes. The output can be a change of properties (e.g. biomass or population size) of some biophysical entities or the maintenance of properties within suitable conditions (e.g. uninterrupted water flow in the river). It can also be a structural modification (e.g. new element in a set-valued property, new living entities) or maintenance of properties (e.g. habitat quality). The process attribute in a function description can point to an elementary process or, more commonly, an aggregate of processes (depending in particular on the granularity required by the analyst). In some cases the function has no apparent process and the function amounts essentially to a structure that prevents some processes being triggered (e.g. avalanche

Function_class
- **name**: *text*
- **is_a**: *pointer-to-entity-classes*
- **bearer**: *pointer-to-entity-classes*
- **input**: {*pointer-to-entity-classes*}
- **output**: {*pointer-to-entity-classes*}
- **process**: {*pointer-to-process-classes*}
- **enabling_condition**: {*pointer-to-predicate-classes*}

Figure 1. A template of the function class (curly brackets denote sets).

prevention or soil retention). The processes are not obvious when they are either slow or no longer active (e.g. old trees and roots with a slow present growth rate). The enabling-condition descriptor points to a set of conditions (predicates) on the input of the subsystem concerned, *i.e.* the current and past state of the subsystem. The realization of the function can occur only if its bearer is in suitable physical state (threshold of effectiveness).

Ecosystem functioning concerns the collective life activities of plants, animals, and microbes, and the effects these activities have on the physical and chemical conditions of their environment. Ecosystem functions determine the capacity of an ecosystem to provide ecosystem services or disservices. A function emerges from the processes operating on a bearing structure. There is a large variety of processes involved in the study or management of ecosystems. They can be physical (e.g. infiltration of water, sediment movement), chemical (e.g. reduction, oxidation), biological (e.g. photosynthesis, nutrient cycling), or ecological (e.g. food-chain dynamics, predation). The loss of the bearing structure implies the loss of the function. The processes involved in ecosystem functions might operate at very fast rate (e.g. photosynthesis) or at very slow rate (e.g. those that create soil or alter soil fertility and groundwater levels).

In agroecosystems, a key ecosystem function is the one responsible for continued plant growth and development. It includes processes such as germination, photosynthesis, respiration and transpiration. The necessary inputs include: light, energy (temperature), carbon dioxide, oxygen, water, and mineral nutrients. The bearer of the function is the plant and the soil or material support of the plant. The enabling conditions include, for instance, soil health. The output of the plant growth function is biomass (e.g. leaves, grains or fruits).

Ecosystem functions can be further classified into groups with respect to their ability to:

- supply nutritional, raw material (e.g. fiber or energy), medicinal or ornamental resources;
- regulate flows (e.g. erosion or avalanches), control pests and diseases, treat waste and undesirable material (detoxify, filter or sequestrate), maintain soil fertility, maintain pollination and habitats for plants and animal nursery;
- maintain aesthetic, recreational, touristic and possibly spiritual resources.

These groups of provisioning, regulation and maintenance, and cultural ecosystem functions are consistent with the proposal of the CICES [23] that proposes the clustering at the level of ecosystem services.

3.3. Ecosystem Services

Biophysical structures and processes in an ecosystem can have functions that provide a service—something that is useful—to people. A service is the work or assistance provided by the ecosystem (or part thereof) to perform the underlying function in the interests of a person or people who are aware and welcome this outcome. The function achieves for these beneficiaries a well-identified benefit that is directly harnessed (direct benefit) or derived (indirect benefit) from the function output. An ecosystem service is therefore defined as much by the context and ecology underpinning the service, as it is by the characteristics of the people benefiting from the service.

Typically, a service (**Figure 2**) involves a function that operates on a part of the ecosystem (a bearing structure) and is perceived by people—the beneficiaries—to provide benefits. For instance, nutrient cycling is the primary process underpinning the function of water purification, which provides clean water to people. Although the dominant outcome of a service is perceived positively, there may also be undesirable side effects. For instance, honey production comes with the risk of bee stings.

For analysis and management purposes, the spatial and temporal descriptors are often critical, hence the properties "location_of_origin", "harnessing_location" and "episode_of_use". A service is also characterized by triggering events that may occur fortuitously (e.g. a climatic event) or as a direct or indirect consequence of decisions made by human agents in the agroecosystem. For instance, consider again the example of a plant growth function, an event related to photoperiods (the relative length of light and dark periods) may trigger a flowering process. A heat shock event may trigger a process of grain abortion. Ecosystem services might be dependent on enabling conditions concerning the bearing entity, living processes and human actors, which are necessary to bring the services into existence and make them enjoyable. In particular, the existence or worth of a service depends on inputs that can be provided endogenously via other services (e.g. natural nitrogen mineralization by which organic N is converted to plant-available inorganic forms) or exogenously by humans (e.g. nitrogen fertilization and labor by farmers). The willingness to satisfy these necessary conditions may drive in part the management behavior of the humans that operate the concerned ecosystem.

Several ecosystem services may depend on the same input. Therefore, a management action that affects this input affects all concerned ecosystem services. Further, an ecosystem service that depends on an input provided by another ecosystem service is potentially affected by any perturbation affecting the latter.

Ecosystem_service_class
- **name**: *text*
- **is_a**: *pointer-to-entity-classes*
- **function**: *pointer-to-function-classes*
- **episode_of_use**: *temporal_type*
- **location_of_origin**: *pointer-to-location-classes*
- **harnessing_location**: *pointer-to-location-classes*
- **trigerring_event**: {*pointer-to-event-classes*}
- **benefit**: {*pointer-to-entity-classes*}
- **beneficiary**: {*pointer-to-entity-classes*}
- **availability_usability_condition**: {*pointer-to-predicate-classes*}

Figure 2. A template of the ecosystem service class (curly brackets denote sets).

Not being affected would be a manifestation of robustness, that is, the ability to replace one input source by another.

In artificial production systems (e.g. crop production in glasshouses) the ecosystemic contribution of the system is very limited because most inputs are exogenous. In contrast, agricultural systems implementing agroecology principles [24] [25] rely heavily on a range of ecosystem services to provide the required process inputs and benefits. More generally, the concept of ecosystem services invites us to look at the ecosystem from the perspective of the multitude of services it can provides, and examine the interaction and co-occurrence in time and space of several ecosystem services that can be in synergistic or antagonistic relationships, or be supplied or demanded together as a bundle of services.

Due to the fact that ecosystem services are primarily functions associated with beneficiaries, they can be structured in pairing with the classification used above for ecosystem functions [23]. Another classification could be built by taking into account the types of beneficiaries [26] and the temporal pattern of harnessing the service. Note that in this paper (as in others), wild biodiversity is considered a cultural ecosystem service. Other types of biodiversity (productive plant diversity, landscape biodiversity) are considered a part of the bearing structure underpinning the desirable ecosystem function, rather than as an ecosystem service per se.

3.4. Disservices

A disservice [27] is a counterpart of service in the sense that it is an ecosystem function whose main outcome is perceived to be undesirable (erosion, habitat loss, nutrient runoff, pest damaging, dispersion of weed) for a person, or people, in particular conditions. Therefore, the concept of a disservice has a similar structure as that of a service (**Figure 3**). Examples of disservices include: promoting invasive species, hosting pathogens or pests, increasing the risk of bee stings, predation by wild carnivores on livestock, or increasing the necessity for using natural resources (*i.e.* water, fuel).

Considering disservices in addition to services is important because they exist naturally or as consequences of human activities. They need to be considered by managers that have to make decisions on the basis of goals that can be either

Disservice_class
- **name**: *text*
- **is_a**: *pointer-to-entity-classes*
- **function**: *pointer-to-function-classes*
- **episode_of_existence**: *temporal_type*
- **location_of_origin**: *pointer-to-location-classes*
- **damage_location**: *pointer-to-location-classes*
- **trigerring_event**: {*pointer-to-event-classes*}
- **damage**: {*pointer-to-entity-classes*}
- **victim**: {*pointer-to-entity-classes*}
- **existence_condition**: {*pointer-to-predicate-classes*}

Figure 3. A template of disservice class (curly brackets denote sets).

positive (desirable situations to bring into being) or negative (prevention or mitigation against undesirable situations). For disservices, managers' interventions should try to prevent the enabling conditions of the undesirable function to be satisfied.

The ontological framework must incorporate both services and disservices in order to be able to account for situations in which people benefit or suffer damages associated to specific uses of natural processes. What is perceived as a service for some may be a disservice for others; presence of wild carnivores is appreciated by those having tourism-related activities but feared by livestock farmers. Moreover, what is a disservice in the short term may be considered a service if looked at over a longer time horizon. For example, a flood, which initially causes destruction, results in fertilization in the long term. Hence, the distinction between an ecosystem service and disservice depends on the context and the perceptions of the actors involved. Finally, note that a function underpinning a service may sometimes come with unintended side effects, blurring the distinction between service and disservice.

The ecosystem services concepts discussed in the section are central but the ontology framework should include several others not addressed here such as benefits, and values of services and disservices, or conflicts and synergies between services.

4. Linking Ecosystem Services to Decision Making

The focus in this section is on the link between ES and the humans that contribute to produce them or that enjoy them at the scale of agricultural regions. The goal is to identify the concepts and relationships that need to be introduced in the ontological framework outlined in Sections 2 and 3 in order to deal with the human dimension of ES in implementing agroecological approaches [25]. An agricultural region is an agroecosystem (see **Figure 4**) and is viewed as social-ecological system [28] with a strong managerial component that is distributed between different actors (farmers essentially but not exclusively) with disparate interests, multiple roles and complex network of relationships. The concept of social-ecological systems was essentially developed [29] [30] [31] in the larger and, therefore, less specific context of policy issues concerning environmental and natural resource problems.

4.1. The Social-Ecological System Perspective

As part of the agroecology movement, researchers and farmers are now looking at agroecosystem sustainability and performance through the lens of ES and their harnessing at different spatial and organizational levels. ES-based management solutions require systemic thinking and a detailed understanding of both the ecosystem and the socioeconomic forces at work, both locally and at larger scales [32]. A large gap exists however between the scientific understanding of ES and its potential use in decision-making practice [6].

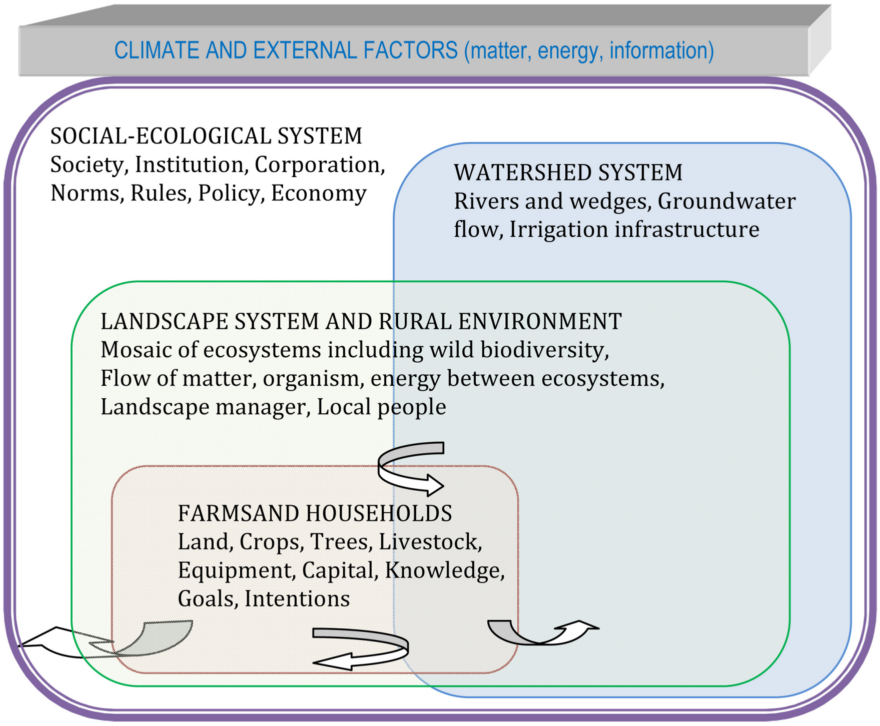

Figure 4. Agroecosystem at landscape and watershed scales within a social-ecological system. The arrows represent flows of services and disservices within and between systems.

Agroecosystems are both providers and consumers of ES [33] [34]. They directly affect many of the very assets on which they rely for success, such as pollination, biological pest control, and maintenance of soil fertility. People value these systems chiefly for their provisioning services, and these ecosystems are designed and managed essentially toward this end. Healthy on-farm ecosystems can also play a role in providing services outside of agriculture, such as wildlife habitat, groundwater quality and aesthetic value of a landscape. Management practices also influence disservices from agriculture, including loss of habitat for conserving biodiversity, nutrient runoff, and pesticide pollution [26]. In agroecosystems, the harnessing and production of ES largely depends on land-managers and farmers' cognitive abilities to understand ecological processes and make management decisions that foster these processes. Further, the human interventions on agroecosystems result from social processes that involve work, capital investment, negotiation involving various stakeholders, as well as cooperation and coordination between actors.

An appropriate ontological framework should support ES-based analysis of how an agroecosystem performs over time, and how it might be changed, both directly by agricultural actors (e.g. farmers, business players) and indirectly by policy makers and civil society. This framework needs to make distinctions between stakeholders; whether they are individuals or groups, whether they depend on the agroecosystem for their professional living or not, and whether they are in a position to act directly on the agroecosystem or only have an indirect influence. It should help characterize and understand the social structures and processes that potentially underpin the effective production, use and distribution of contextual knowledge about ES and disservices over time, space and situations.

In the following sections, we visit the essential categories needed to address social-ecological and socio-technical issues in local agroecosystems, with focus on human decision-making at both individual and collective levels. The proposed ontological framework of social-ecological systems represents the categories as assemblages of entities, events, or processes. The entities include those already considered in the preceding sections.

4.2. Individuals as Farm Managers

In the study of ES-based farm management the central conceptual modeling construct is the individual human agent [35] [36], an entity capable of manipulating and reasoning upon mental and abstract representations. To understand the behavior of an individual, one needs to examine her/his cognitive capabilities and the decision-making mechanisms in which these capabilities are mobilized [37]. An individual agent has the ability to observe the environment and acts deliberately based on her/his goals, her/his beliefs, her/his intentions of actions, and her/his preferences or personal values; these concepts are also entities in the ontological framework. The agent's beliefs correspond to the informational state of the agent after observation or reasoning from evidence. Beliefs include possibly erroneous knowledge the agent has about the processes that govern the change of biophysical variables. Since beliefs can be incomplete and incorrect they are updated or revised as new facts and supporting evidence are acquired. A goal is a combination of desired system features indexed by time. A goal may correspond to a personal aspiration (e.g. maintaining the possibility to enjoy the farming way of life) or the development of a high-level production goal (e.g. ensure sufficient profit) into more specific subgoals (targeting of raw production and marketing, enhancing ecosystem services, avoiding peak labor demand). An intention [38] is a commitment of the agent to realize particular goals by applying a specific plan that organizes future actions in a flexible way. The flexibility of intentions refers to the possibility of a situation-dependent choice of actions, including flexibility in the timing and resources used in their execution [39] [40]. Preferences are internal criteria used for evaluation of alternatives or for filtering the candidate goals, plans, and data to examine closely in particular situation. In a decision-making approach that aims at articulating actions with ES (and disservices) considerations the preferences must relate to the notion of value of services and disservices. Preferences also incorporate attentiveness to the social norms of the groups that the agent is associated with (friends, family, or partners) as well as very practical or personal predilection for some ways of acting over others.

Many cognitive processes are involved in the farmer's management activity, including monitoring, interpretation of data (sense making and diagnosis), prediction, goal formation, planning (including land-use design), and scheduling [36]. They are still poorly understood and insufficiently studied, although they have an essential role to play in developing a more sustainable and service-oriented agriculture. Sense-making concerns the detection of contextual details that might influence decisions. The information gathered by the farmer is only useful once it is transformed by him into situation awareness, that is, an understanding of the current situation (hindsight) and anticipation of how this situation might evolve (foresight). When the farmer cannot observe the biophysical state directly or accurately enough, she/he may try to construct a cognitive representation of the actual situation using a mental model. Monitoring aims at detecting significant events that may trigger or reactivate various cognitive processes involved in the decision-making process. In addition to noticeable changes detected through sensors or visual observation, events may come from the manager's mind, or from the external environment (meteorological or pest attack alert). For example, the adoption of a new goal constitutes an event that triggers planning, which can subsequently trigger a commitment decision to enact the plan. Planning involves constructing or discovering appropriate actions that are expected to lead to a situation being more desirable than otherwise. Planning is also a means to anticipate the future, and to guide and organize future activities. Crop rotation is an example of land use planning spanning several years. Seasonal organization of cultural activities and management of rotational grazing on a set of pastures are examples of planning over a several month horizon. Deriving actions from a plan requires a scheduling work to determine what should be executed given the available working resources (e.g. labor, machinery) and the current priorities and preferences.

The service-focused management approach is still in its infancy, which precludes full formalization at this stage. It invites farmers to be as holistic as possible in their analysis of the system, and to have an integrated view across many components of the farming system. It also encourages them to identify management actions that can take advantage of potential synergies and find optimal compromises when necessary. Achieving this objective is hampered however by the inherent complexities of ES that conflicts with the limited cognitive capabilities of humans. Managers, especially farmers, have developed bounded rationality behaviors [36] [41] that enable them to make efficient decisions with less than complete information. Such an approach is necessary to make the decision problem tractable, and to cope with partial understanding of the biophysical basis and ecological interactions, the lack of perfect foresight, and the required ability to adapt to fluctuating conditions. The question remains if and how farmers can accommodate the extra complexity brought in by a service-centered management philosophy and what indicators, operational targets and heuristic knowledge might help to cope with this added complexity.

4.3. Groups, Corporations, Institutions

Among the important constructs (entities) in a social ontology [42] is the concept of groups, and the relationships between agents in a group. A group gathers individuals who share some concerns at a particular point in time. Each case study involves many social agents with disparate interests, a multiplicity of roles, and complex networks of relationships that require a high level of abstraction for analysis. The formation, persistence and dissolution of groups largely depend on interactions between the members. Of primary importance are the relationships that concern information sharing, collective target setting, consensus finding, coordination of actions, and material resource sharing (mutual help). Indeed, members of the group are chiefly tied by common goals and, in some cases, actions done cooperatively or coordinated towards these goals. In a group, all the members benefit from the satisfaction of the group goals, even if for different reasons. Some people may belong to more than one group, and this can sometimes cause conflict. What happens at the regional scale of an agroecosystem is an amalgamation of actions taken by heterogeneous agents (mostly farmers and land managers) that exhibit autonomous behaviors influenced by other people and events. In the case of a joint goal, it may not be enough that agents control their own actions, *i.e.*, correctly predict their effects, monitor their execution and make adjustments if needed. They may also need to anticipate and monitor their partner's intentions and actions, predict their expected consequences and use these predictions to adjust what they are doing to what their partners are doing [43]. Examples of group in social-ecological systems include: 1) a community of people living in a region, 2) a lobby group of people, such as a consumer organization strongly supporting a particular cause, or 3) an organization of farmers that engage in collaborative work.

A corporation is a stable agent socially constructed and organized for a business-oriented purpose. It might be structured in sub-organizations (functional areas, departments) and roles assigned to agents. In order to make those agents stick to their role they are subject to internal obligations. At the same time, the organization, as an agent, can be subject to obligations too (it is a so-called legal person). Examples of corporations include input retailers, extension services, agro-food processing, large food retailers and large farms with employees.

An institution is a non-profit stable entity that provides informational or cognitive support, and incentives or barriers to particular types of behavior through norms (e.g. standard modes of business protocols) or obligations (regulatory frameworks, property rights). Institutions can also be defined from a more social and cultural perspective, to include informal conventions, habits, behaviors and routines of individuals or small groups of people. It is a structure of social order. It governs the behavior of a set of individuals within a given community. Norms and obligations tell people what they ought to do in a given situation. Institutions both constrain behavior, by defining socially acceptable ways of acting, and enable behavior, by providing agreed-upon social norms, which do not need to be continuously negotiated. They are enforced externally but emerge to some extent from the society. Institutions include state agencies such as landscape managers, research organization, and political authorities at different levels.

The main group and corporation-related processes concern communication, goal formation, consensus finding (trade-off between desires of stakeholders), negotiation, coordination, monitoring of action effects, and social learning. Institution-related processes include establishing regulations and incentives, organizing debates, and ensuring agents meet their obligations. Events that drive social dynamics include all events related to: policy-related changes (regulation, taxes, incentives), structural changes to an agroecosystem (e.g. new agribusiness actor), outbreaks of conflict situations between stakeholders, changes of management regimes by some farmers, and service-related achievements associated with particular management practices of collective interest.

Social networks (groups of groups) play an essential role in spreading knowledge and new behavioral principles across groups in a cascade dynamics. The proposed ontological framework could be employed to characterize social networks and analyze: the existing or lacking relationships, the nature of the flows that they support, and the decisions that result from the interactions within and between groups. It could help to reveal weak spots in the way individual and collective agents behave, and identify the cause of underwhelming results (e.g. insufficient knowledge, lack of resources, inappropriate incentives, inadequate practices).

5. Conclusions

Effective ES-based thinking in agriculture depends on a clear understanding of the interactions among the biological, physical, and socioeconomic aspects of the services that stakeholders are motivated to produce and/or enjoy. The ontological framework sketched in this paper provides a concise and precise consolidation of structural and behavioral features of agroecosystems viewed as social-ecological systems. By promoting a common understanding of agroecosystems the framework constitutes the foundation of an epistemological tool or a metamodel in the sense of an abstract conceptualization that can be instantiated for any specific agrecosystem. Its broad scope organized along the three familiar concepts of entity, process and events helps build the capacity of individuals and institutions to discuss, understand, monitor, manage and design agroecosystems thought in terms of ES. The human aspects contained in the framework support investigation and learning about the principles guiding situated decision-making behavior of actors, rational building of goals and management strategies at both individual and collective levels, and elaboration of technical practices coherent with ES-oriented agriculture.

Much work lies ahead to refine the concepts presented in this paper and to ensure that they are applicable to developing large models covering the full social-ecological spectrum required by landscape and agroecosystem projects. The ontological framework is not about a stabilized objective world, especially because its scope includes social conventions and human perception. Concepts, meanings and interpretations are relative to the concerned community and can change over time, especially when the community boundaries move. Moreover, the way in which the ontology is accepted is similar to the way a scientific theory is accepted; that is, by seeking to accommodate new facts and views in the domain until a paradigm change becomes necessary. Therefore, it is anticipated that ontology enrichment will be needed as experience with ecosystem services and social-ecological systems grows.

The capacity for the described concepts to be incorporated as primitives in an agent-based modeling platform [44] is the challenging next step. The objective is to develop a powerful simulation framework in which existing agroecosystem situations can be represented and computational experiments performed to explore hypothetical management scenarios and uncover critical biophysical and decision behaviors in agroecological research.

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