A framework for vulnerability assessment in extensive agro-pastoral landscapes of Europe

MANUSCRIPT UNDER REVIEW: DO NOT CITE OR CIRCULATE

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Abstract

We propose a framework for vulnerability assessment that links ecosystem services identified and valued by stakeholders with an ecological characterisation of prospective land-use change in European agro-pastoral landscapes principally using plant functional traits. The methodology uses five matrices that quantify, link and integrate social and biophysical information. We illustrate the framework using some preliminary findings from two study sites, Col du Lautaret in the French Alps and Mértola in the Portuguese Alentejo region. This framework provides a quantitative, contextual, place-based approach for assessing vulnerability. The use of social surveys with selected stakeholders to identify and value ecosystem services sets the social context for translating the biophysical assessment of ecological change into an evaluation. The framework accommodates a full range of stakeholders and ecosystem services, where both can be classified and weighted as appropriate. Multiple, differing values can be placed on the same ecosystem service by different stakeholders. The five matrices provide a transparent and flexible means of quantifying, linking, and evaluating the biophysical and social information. These matrices also articulate two important, often neglected links between ecosystem services and the underlying ecological attributes that contribute to those services. The first of these is to link ecosystem services with a range of physical elements (descriptors) in the landscape that stakeholders consider as important to the delivery of the ecosystem services. The second is to link these descriptors with underlying ecological attributes that ecologists consider to contribute to the delivery of the ecosystem services. The framework allows a wide range of vulnerability assessments to be performed in a variety of regions, where these regions may be composed of very different stakeholders that identify and value very different sets of ecosystem services.

Key words

Vulnerability assessment, ecosystem services, traditional European agricultural landscapes, social values, plant functional traits, land-use change, global change scenarios.

Introduction

As well as providing a range of food and fibre products, low intensity, extensive agro-pastoral landscapes in mountain, Mediterranean, cold and otherwise marginally productive regions of Western Europe provide a diversity of other ecosystem services. These include recreational, aesthetic, inspirational and wild flora and fauna conservation services. However, technological, social and other economic changes have resulted in, and continue to bring, significant land-use change in these landscapes (Baldock et al. 2002). An overall reduction in agricultural land through 'abandonment' and/or changes in intensity and type of use have transformed the former mosaics of a range of land-use intensities to coarse-grained mosaics where large abandoned areas are contrasted with foci of intensive use (MacDonald et al. 2000; Schmitzberger et al. 2005). Changing land use patterns and practices can greatly affect the delivery of ecosystem services by modifying both the structure and functioning of ecosystems (Chapin et al. 2000, Foley et al. 2005). The range of services provided by these landscapes are being increasingly valued (Aitchinson 1995), with farmers being subsidised to maintain the agricultural practices that contribute to the delivery of such services (Kleijn and Sutherland 2003, Penker 2005). Most marginal agricultural areas in Europe are also classified as Least Favoured Areas and given specific financial support within the European Common Agricultural Policy. Such policy intervention requires scientific assessments of the impact of land-use change on the delivery of the range of services provided by these landscapes (Foley et al. 2005).

In this paper, we frame the identification and evaluation of changes in the provision of ecosystem services by these landscapes in terms of vulnerability. The concept of vulnerability has recently received increasing attention within the global change area as an innovative evaluation method of ecosystem change (e.g. Kelly and Adger 2000, McCarthy et al. 2001; Turner II et al. 2003a; Downing and Patwardhan 2003, Schröter et al. 2006). There is a growing recognition that biophysical assessments of vulnerability need to be placed in a social context, as these assessments involve value judgements about the identification of important ecosystem services and of the acceptability or otherwise of ecosystem change (Füssel and Klein, in press; Millennium Ecosystem Assessment 2005). There is also a recognised need to make progress in the development of quantitative methods for vulnerability assessment (Luers et al. 2003; Metzger et al. 2005). As a result, recent research has strived to develop frameworks that are able to integrate the social and biophysical dimensions of vulnerability, and provide better quantitative methods to do so (Klein and Nicholls 1999; Schröter et al. 2005; Turner II et al. 2003b, Cundill et al. 2005; Millennium Ecosystem Assessment 2005).

Building from a biophysical research perspective, we propose a conceptual framework and associated methodology for vulnerability assessment that represents progress in both of these areas. Our approach is comparative, where we compare the relative vulnerability of a selected set of stakeholders and associated ecosystem services at a particular place, with the vulnerability of other sets of stakeholders and associated ecosystem services at the same or in different places. The framework has been developed as part of the VISTA project ('Vulnerability of ecosystem services to land-use change in traditional agricultural landscapes'[1]), which examines vulnerability to projected changes in land use by 2050 at 11 study sites across Europe's mountain, Mediterranean, cold and otherwise marginally productive regions. Our definitions of vulnerability and associated key concepts are presented first, for application to prospective future changes in ecosystem services provided by agro-

[1] http://lotus5.vitamib.com/hnb/vista/vista.nsf/Web/Frame?openform

pastoral landscapes. We then present the conceptual framework, where stakeholder assessments of ecosystem change are accommodated conceptually through the introduction of the concept of ‘acceptability’ into the formulation of vulnerability, and practically, using social surveys with stakeholders to identify and value ecosystem services. We then illustrate the concepts and methodology using some preliminary findings from a subset of social and ecological data gathered at two of the VISTA study sites, the Col du Lautaret in the French Alps and Mértola area in the Portuguese Alentejo region. Rather than providing exhaustive assessments of these sites, the findings and comparisons are provided principally as a means of demonstrating some of the features of a more generally applicable framework for vulnerability assessment. The framework can be modified and adapted as appropriate to suit the needs of different studies of vulnerability concerned with changes in ecosystem services. The results presented here are therefore not intended to represent formal vulnerability assessments of these sites, and hence a wider discussion of the implication of these findings for European vulnerability to projected global changes is not included. Future publications from the project will address these aspects.

Definitions

As shared by other definitions of vulnerability in global change research, we understand vulnerability as being the compound result of exposure, sensitivity and adaptive capacity (e.g. McCarthy et al. 2001; Turner II et al. 2003b; Metzger et al. 2005; Füssel and Klein, in press). Our definitions of exposure, sensitivity and adaptive capacity in relation to the delivery of ecosystem services are taken or adapted from definitions proposed by McCarthy et al. (2001) and Metzger et al. (2005). We include an additional concept of ‘acceptability’ to explicitly accommodate stakeholder judgements of ecosystem change. Our set of definitions for vulnerability are described below. Definitions of other key concepts are given in Appendix 1.

Exposure is the nature and degree to which ecosystems are exposed to environmental change. We represent exposure in terms of a range of scenarios, similar to a range of other international assessments (McCarthy et al. 2001, Millennium Ecosystem Assessment 2005).

Sensitivity is 'change in the selected ecosystem services at a given site in response to exposure' (Metzger et al. 2005).

Adaptive capacity is the ability of a system to adjust to global change (including variability and extremes) to moderate potential damages, to take advantage of opportunities, or to cope with the consequences. Here, we chose to approach adaptive capacity in terms of acceptability, representing one possible social measure of adaptive capacity (adapted from McCarthy et al. 2001).

Acceptability represents stakeholders' judgements about changes in identified ecosystem services as a response to exposure. Acceptability can be variously assessed in terms of a single ecosystem service, a subset, or the full set of, ecosystem services, and by a single stakeholder, a subset of, or by all stakeholders.

Vulnerability represents the comparison of acceptability of change in ecosystem services, as a response to exposure for all selected scenarios. Comparisons can be within site, comparing between stakeholders or sets of stakeholders, as well as across sites. However the comparison must include all scenarios to take into account the full range of measured exposure. We note that our approach is necessarily comparative, this approach is further developed in the discussion.

A framework for assessment of vulnerability

The VISTA framework integrates biophysical and social information by explicitly linking ecosystem services of traditional agricultural landscapes identified and valued by stakeholders, with a combined ecological and land-use characterization of landscape change. We use a combination of ecological field studies, landscape modelling, land-use modelling, and social surveys to achieve this. Figure 1 illustrates the overall structure and flow of information of the framework. A brief overview of the framework is presented below, with a detailed description and illustration following based on some preliminary findings from the two study sites.

Five matrices are used to quantify, link and evaluate the biophysical and social information at each study site. These matrices are explained in detail in the following section. Exposure is represented in terms of prospective changes in land-use under plausible land-use change scenarios. Land-use changes are quantified in terms of changes in land-use attributes and associated changes in functional attributes (*sensu* Gitay & Noble 1997) of the vegetation. This data provides the initial input data into the framework. Sensitivity is estimated via two additive pathways. The first pathway (illustrated on the left of Figure 1) links changes in ecological structure and function to changes in ecosystem services. To do this it estimates the contributions of changes in PFT, ecosystem attributes and descriptors to changes in ecosystem services using the corresponding matrices. The second pathway represents a more simplified pathway and links changes in land-use and land management with changes in ecosystem services. Do to so, it uses the land-use attribute matrix and the descriptor matrix to estimate changes in ecosystem services. The two pathways are complementary and additive, and account for the fact that ecosystem attributes alone can not account for all descriptors used by stakeholders. Adaptive capacity is then measured in terms of acceptability. Acceptability is calculated by coupling projected cumulated changes in the delivery of ecosystem services through the two pathways with the ecosystem services matrix. Vulnerability is then assessed for selected groups of stakeholders within a site or across sites.

For the purposes of this paper we have used the simplest rating or measuring scales to illustrate the framework. However, the framework can accommodate more sophisticated scales, this is further addressed in the discussion section.

Study sites

Col du Lautaret

The Col du Lautaret (Lautaret herein) study site is the south facing slope above the village of Villar d'Arène in the central French Alps (45.04°N, 6.34°E). The slope extends from approximately 1650 to ca 3000 m altitude. The climate is sub-alpine with a strong continental influence due to neighbouring mountain ranges intercepting rain accompanying the western winds. Mean annual rainfall is 956 mm and the mean monthly temperatures at 1650 m (lowest point in the study site) range between -2.6°C in January and 13°C in July. At the upper limit of former arable land-use (2050m) temperatures range from -4.6°C in January to 11°C in July. The site is located within the buffer zone of the Ecrins National Park and a Natura 2000 conservation network designated area. The main activities in the area include animal husbandry, nature conservation, and recreation. We focus our study on a mosaic of grasslands between 1650 and 2100 m, with varying past and present land-use. We term these existing combinations of current management with past land use (and the land-use changes described below for Mértola) as 'land-use trajectories' hereafter. These land-use changes affect nutrient availability (mainly through organic fertilisation) and disturbance regimes (mainly through mowing and seasonal grazing) (Quétier et al. submitted b). As in many marginal agro-pastoral areas in Europe, recent socio-economic changes have lead to a decrease in management intensity. This includes a reduction in the fertilisation of hay meadows, a shift from hay making to light grazing by sheep or cattle, or abandonment of agro-pastoral activities. These changes in grassland management are associated with significant changes in floristic composition and representation of different plant functional attributes (Clément et al. 2003; Lavorel et al. 2004).

Mértola

The Mértola site is located in the south east of the Portuguese Alentejo region. This area is hilly, with poor, shallow soils and has a typical Mediterranean climate, with long dry summers and humid winters (Perez 1990). Due to these biophysical conditions in combination with its relatively remote location and historical factors, the whole of the Mértola region is currently considered to be one of the most marginal agricultural areas in Europe.

Traditional agro-sylvo-pastoral systems, called Montados (Pinto-Correia 1993) are managed open woodland-savanna ecosystems where evergreen oaks are managed for cork and/or acorn production. These Montado systems are one of the main land uses in the area, accounting for 30% of the total area. The understorey of the Montado woodland is managed using a range of different grazing and cultivation regimes, resulting in a shifting pattern of arable land, grassland, unmanaged pasture and shrubland.

During the last few decades major land-use changes have taken place in the area due to changes in the local socio-economic and demographical structure and to the implementation of the Common Agricultural Policy (Van Doorn 2004). Overall, land-use in the Mértola study site has been following an extensification trend. Agro-pastoral abandonment, reduced grazing pressure and the cessation of arable rotations has led to increased shrub encroachment. Since the 1990s large areas of Montado woodland (including both abandoned and non-abandoned areas) have been also converted to forestry plantations.

Social survey methods

Semi-guided interviews were conducted at both sites in spring and summer of 2004. These interviews aimed to identify the range of relationships (e.g. in terms of uses, roles, activities and representations) selected stakeholder groups currently have with their respective landscapes. Methods differed at each of the sites, and a brief description of each is provided below taken from (Quétier et al. submitted a) and (Oliveira and Pinto-Correia, submitted) respectively. In both cases, interview participants were not directly asked to identify or value an ‘ecosystem service’ or a ‘descriptor’. Rather, ecosystem services and descriptors were represented in terms that were more familiar to the interview participants such as in terms of uses, factors of importance, roles or values.

At Lautaret, 45 interviews were conducted. An interview guide was used to lead the interview from a description of the overall landscape through to a discussion of more detailed descriptions of the local grasslands. The first part of the interview aimed to generate a minimally prompted description of the overall landscape by asking participants to describe the local site and scenery in whatever terms they wished. If needed, additional questions prompting views on the identification of specific or unique local landscape elements or to re-launch the discussion were asked. The second part of the interview focused on the local grasslands: their vegetation (e.g. presence of particular species, horizontal and vertical structure, color), their variations in space (across the landscape) and time (through the seasons), as well as their identified uses and other values by interviewees themselves or by other stakeholders. To help elicit these descriptions and values, example photographs illustrating different types of grasslands at different seasons and in different landscape configurations (e.g. grazing and mowing) were presented to the interviewees. We used a series of pictures taken in four different landscapes between April and August, 2004. Interviews were recorded and the terms used by interviewees to describe the grasslands as well as the corresponding uses and representations were identified and listed as either positive, negative or neutral (or absent) for each interview. A subset of terms used to describe grasslands and the corresponding uses and representations that were shared across a stakeholder group were chosen to illustrate the proposed framework. We chose 3 stakeholder groups (respectively hikers, farmers and the National Park Authority) to illustrate the proposed framework. Descriptors only represent a subset of all the terms used by interview participants to describe local grasslands at Col du Lautaret. Ecosystem services also represent a subset of the uses and representations that were valued by interview participants. By design, the relationships between descriptors and ecosystem services were common across all interviews groups producing a single descriptor matrix for the site.

A hundred and twenty three interviews were conducted at Mértola aimed at soliciting the views of a wide range of residents, owners, visitors to the region, and decisionmakers including resident and non-resident farmers, land owners, hunters and visitors. The interview guide consisted of a number of parts, with only a subset of the data being used for this study, these parts only are described here. The first part focused on landscape 'descriptors', asking the interviewees to describe the local landscape and identify the range of relationships they had with it. The second part focused on preferences for different types of landscapes where photographs of different types of landscapes within the study area were shown. Interview participants were asked to rank the landscape types from highest to lowest preference and explain their ranking choice. The analysis of the interview data used both descriptive (percentages and frequencies) and factorial statistics (multiple correspondence analysis) to see if any relationships existed between sets of stakeholders and the set of identified uses and other values. Stakeholders and ecosystem services were grouped similarly to the method used in Lautaret, except stakeholders groups were more restricted, based on shared activities only. As with Lautaret, we selected a subset of shared values to present for each of the stakeholder groups for the ecosystem service matrix and across all stakeholders for the descriptor matrix.

For the purposes of this paper we only present a small sub-set of the findings from these social studies, focusing on a restricted set of widely known services and groups of stakeholders. The data presented here is based on interviews with 7 farmers, 10 hikers and a representative from the National Park Authority for Lautaret, and 35 farmers, 14 hunters and a representative from the Natural Park Authority for Mértola.

The five matrices

The VISTA framework uses five matrices to quantify, link and evaluate the biophysical and social information. Three types of matrices can be distinguished based on the type of information they contain. The first type, represented by two matrices, the *ecosystem service matrix* and the *descriptor matrix*, contain information obtained using social surveys. The second type, represented by one matrix, the *PFT matrix,* contains information obtained through ecological field measurements. The third type, represented by two matrices, the *ecosystem attributes matrix* and the *land-use attributes matrix*, links ecological data obtained through field measurements or land-use data modeled from the scenarios to the descriptors identified through social surveys. The matrices are described in detail below and are illustrated in Figs. 3-4 using some preliminary findings from the two study sites. All five matrices and other information are presented for Lautaret, with all information except the *PFT matrix, ecosystem attribute and land use attribute matrix* presented for Mértola.

Ecosystem service matrix

The ecosystem service matrix links stakeholders with selected ecosystem services (Figs. 3a-b). This matrix represents the selected community of interested parties and defines the boundaries of the human system. Individually and collectively the views synthesised in this matrix represent a social evaluation of ecosystems, in relation to their current state and projected changes. Values represent how stakeholders currently value each ecosystem service, and are in this example rated on a three point Likert (Likert, 1932) scale (- = negative, 0 = not important, + = positive). This information is compiled from individual interviews and questionnaires, as described above. A range of different stakeholder classifications can be developed based on socio-demographic criteria (e.g. age, education, length of residency status), shared uses or activities (e.g. food or fibre production, photography) or particular sets of shared ecosystem services (e.g. a ‘heritage’ discourse, see Quétier et al. submitted a). The classification presented here was based on uses and consists of two shared groups across the sites: farmers and a conservation agency, and two unique groups; hunters and hikers at Mértola and Lautaret respectively. Services presented here include cultural services (agro-pastoral scenic value and wild beauty), production services (hay making and honey production) and biodiversity services (abundance of game, habitat for fauna). We assigned how each stakeholder group valued each ecosystem service in the following manner. A positive value (+) meant that stakeholders valued the service positively. This was for a range of reasons. These reasons included directly carrying out (and benefiting from) an activity, someone else carrying out an activity that was beneficial to the stakeholder, or holding a positive representation of the region, not related to any specific activity. For example, at Lautaret, local farmers cut grass for hay and valued hay for winter fodder positively. The National Park Authority stated that hay for winter fodder was essential in maintaining the authentic rural character of the site and also valued it positively. Local farmers in Mértola valued positively the agro-pastoral scenic value of the Montado understorey for similar reasons. At Mértola, hunters valued positively the abundance of game. At Lautaret, the National Park Authority valued all ecosystem services positively (wild beauty of the landscape, hay for winter fodder and habitat for fauna) as, in addition to their primary conservation objective, they were interested in accommodating the range of activities and landscape representations that are generally held of the region.

A null (0) value meant that the stakeholder didn’t carry out the activity and the activity was not perceived as having any effect on the ecosystem services they valued, or they didn't think this service was important. In Mértola, hunters valued agro-pastoral scenic value and honey production game neutrally. Hikers at Lautaret valued hay for winter fodder and habitat for fauna neutrally. These ecosystem services are not considered important for their recreation activities and although there were some exceptions in survey participant responses in interviews, the maintenance of landscape aesthetics such as the wild beauty of the landscape were generally not considered to be related to agricultural activities such as hay for winter fodder (where in fact this activity is critical to maintain the present open landscape). This highlights the fact that stakeholders won't necessary make causal links between values placed on different ecosystem services. A neutral value can also be assigned where there is a mixed opinion within the group of stakeholders, where on average the stakeholders value the ecosystem service neutrally.

A negative value (-) means that an activity or a representation of the region was seen as having a negative effect on other services rated as positive by the same stakeholder. For example, at Lautaret, local farmers valued the wild beauty of the landscape negatively, one reason being that it attracted hikers who walk across their fields apparently unaware that the landscape is managed by farming and trample the grass used for hay for winter fodder. At Mértola, the Natural Park Authority valued the abundance of game (such as wild boar) negatively, these animals currently having a negative impact on the flora (and other fauna) of the Natural Park.

Descriptors matrix

The descriptors matrix links biophysical and land-use descriptors to the ecosystem services selected by stakeholders (Figs. 3c-d). Descriptors represent the cues that stakeholders use to judge the delivery (or potential for delivery) of each ecosystem service. Values represent either a negative (-), neutral (0) or positive (+) relationship with service delivery, and are derived from the social surveys. Depending on the ecosystem service, a range of different physical descriptors may be selected, with the contribution of each of them to this service being weighted as positive, neutral or negative. The descriptors that stakeholders consider important may or may not have an ecological contribution to the actual delivery of the ecosystem service. They also may or may not represent an ecological attribute. This matrix represents an important, often neglected link between identified ecosystem services and identified physical landscape elements (descriptors) that contribute or otherwise to the delivery of the ecosystem service.

In our example sites descriptors included biophysical elements (e.g. variety of flower colours, the abundance of plant types such as unpalatable grasses, or shrub density) and physical land-use elements (e.g. visual cues of agricultural activities or the presence of grazing livestock) that survey participants focused on in their evaluation for each of the selected ecosystem services. Descriptors presented here represent descriptors that were common to all stakeholders. For example, at Lautaret stakeholders related hay for winter fodder to grassland productivity and the abundance of legumes (positive relationship with service delivery) and to the abundance of unpalatable plants (negative relationship). Visual cues of agricultural activities and the open nature of the landscape were also related positively to hay for winter fodder. At Lautaret, the wild beauty of the landscape was related to the variety of flower colours and the open nature of the landscape (positive relationship) and negatively related to visual cues of agricultural activities.

Ecosystem attributes matrix

The ecosystem attributes matrix links the biophysical descriptors used by stakeholders to assess an ecosystem's capacity to provide a given ecosystem service to underlying ecosystem attributes as identified by ecologists (Fig 4a). This matrix represents another important, often neglected link between ecosystem services and the ecological attributes that contribute to the delivery of the ecosystem service. This matrix links the social context of how and why the environment is valued to the biological context of underlying ecological processes and attributes that contribute to the delivery of the ecosystem service. Values represent a proven or inferred causal link between ecosystem attribute and descriptor, ranging from positive (+) negative (-) or no causal link (0).

Linking stakeholders' knowledge (descriptors) to scientific understanding of ecosystem structure and ecosystem processes (grouped under the common label of ecosystem attributes) can be straightforward, such as the case when the biophysical descriptor also represents an ecosystem attribute. At Lautaret this applies for instance to grassland productivity, which is directly measurable, or to the abundance of unpalatable plants, which can directly be linked to the abundance of *Festuca paniculata*, an large and unpalatable tussock grass. In other cases, making these links requires some interpretation. For example, to link available ecological data to the variety of flower colours, we constructed a 'flowering diversity index' using data from the literature on flower size and colour and ecological field data on the abundance of flower species and their time of flowering (Clément et al. 2003, Thébault 2004).

Land-use attributes matrix

The land-use attributes matrix links land-use attributes to land-use descriptors that stakeholders identify as being important to the delivery of each of their selected ecosystem service(s) (Fig. 4b). As discussed for linking ecosystem attributes and stakeholder descriptors, some interpretation is necessary to relate land-use attributes and stakeholder descriptors. Some are straightforward, e.g. organic fertilization and flock size providing visual cues of agricultural activities in Lautaret, while others are less obvious and require some knowledge of the local socio-ecological system, such as flock size contributing to the openness of the landscape (MacDonald et al. 2000, Baldock et al. 2002). The distinction between descriptors related to land-use attributes and those related to ecosystem attributes is made on the basis that only the latter require ecological understanding of underlying processes.

PFT matrix

This matrix links plant functional traits (PFT) to the ecosystem attributes that are identified as relevant to the delivery of the selection of services (Fig. 4c). We chose to include PFTs in this framework because they can provide general relationships between environmental change, vegetation composition and ecosystem properties (Gitay & Noble 1997, Lavorel et al., 2005). They are easy to use both for modelling ecosystem change (e.g. Cousins et al. 2003, Grigulis et al., 2005) and for developing easily measurable indicators in the field (Ansquer et al. 2004). As such they provide a useful general tool for making projections of changes in ecosystem attributes on the basis of land-use change scenarios.

The relationships presented in the matrices are the direction of correlations between given ecosystem attributes and one or several plant functional traits. The traits that are used for the vulnerability assessment are preferably 'soft' traits, which can be measured easily and at limited cost on large numbers of plant populations, yet have known relationships to plant function and associated physiological or demographic characteristics (Hodgson et al., 1999). In the simplest case, some ecosystem attributes that represent biophysical descriptors for specific ecosystem services may simply equate to plant functional traits. An example of this could be sward height (an indicator of fodder quantity), which can be equated to community-level plant height (no such example is used in the matrices used to illustrate the framework).

Other relationships represented by the PFT matrix are obtained from field surveys that involve the measurement of PFT on plant populations present in different land-use trajectories using standardised methodologies (Cornelissen et al. 2003), and quantification of ecosystem attributes in each trajectory. For instance, aboveground primary productivity is estimated using sequential harvests of live and dead biomass (Scurlock et al. 2002). The significance of relationships between ecosystem attributes and PFTs are then tested by statistical methods such as stepwise regression (Garnier et al. 2004). At Lautaret, grassland primary productivity was related to leaf traits including leaf phosphorus concentration (LPC) (positive association), and leaf dry matter content (LDMC) (negative association). These traits themselves respond to phosphorus fertility and the abundance of *Festuca paniculata* (Quétier et al. submitted b). Similar relationships (positive for LDMC and negative for LPC) were found for the abundance of *Cistus ladanifer* in Mértola Helena Castro, unpublished results). Such relationships should preferably be obtained for each site, because they may vary depending on a range of factors such as site productivity (Adler et al. 2004), climate (de Bello et al., 2005) or local land-use history (Milchunas et al. 1988).

Quantifying exposure

Scenarios of land-use change

Many marginal agricultural areas of Europe have undergone a process of extensification in the second half of the 20th century, accelerating the decline of traditional labour intensive agro-pastoral practices. For the purposes of this paper, we present two scenarios of prospective land-use changes at each of the study sites: a) a renewal of the current declining agricultural practices by providing additional support that favours intensification of management (‘staying tame’ hereafter), and b) a continuation of current trends of extensification and agricultural land abandonment (‘going wild’ hereafter). Being considered equally plausible (Rounsevell et al. 2005), they are used jointly to project the range of possible effects of changes in agricultural policy options in Western Europe (McCarthy et al. 2001, Baldock et al., 2002). Each scenario is formulated in terms of a set of land-use trajectories projected to occur over a specified proportion of area at each study site. Land-use change trajectories can be shared across scenarios for a given site, however may occur over a different proportion of area (e.g. the abandonment trajectory at Lautaret). Land use trajectories were modelled and represented in terms of land use attributes. Changes in PFT composition of vegetation were projected using statistical models (e.g. Kleyer 1999; 2002), point simulation models of vegetation succession (e.g. Quétier et al. submitted c) or landscape dynamic models (e.g. Cousins et al. 2003). The latter can be used in combination with a spatially explicit approach where the spatial distribution of land-use trajectories might be mapped using a variety of GIS-based modelling tools (Verburg et al. 2002). In the examples presented here, we focus on the relative proportion of the total area at each site that is projected to change for each land-use trajectory. We used results from statistical models to relate land-use change trajectories to changes in PFTs at both sites (Lavorel et al. 2004; Quétier et al. submitted b; Castro et al., unpublished data.). Scenario data are presented in Table 6 and Appendix 1d.

Scenarios for Lautaret

In European mountains, traditional mowing practices have been disappearing together with farmers and their flocks. Sub-alpine grasslands of areas such as the Lautaret are increasingly abandoned or converted to extensive summer grazing (MacDonald et al. 2000). Effects of extensified grassland management on PFT and ecosystem attributes at Lautaret were quantified from observation on ongoing land-use change and results are used here to translate the effect of scenarios (Quétier et al. submitted b, Thébault, 2004). The staying tame scenario is principally based on an increase in current levels of financial support provided to maintain the economic viability of existing farms. Through an increased provision of funding to reverse current extensification trends, intensification of the most accessible grasslands is projected to occur (‘fertilisation’ trajectory, representing 2/3 of the total area). This more intensive management would require increased inputs such as organic fertilization and use of machinery. This would favour taller plants with faster growth rates as indicated by functional traits such as increasing LPC and decreasing LDMC. By increasing evenness in species abundances in the plant community where no single species is overly dominant, organic fertilization would also favour an increase in the variance in flowering phenology. The remaining grasslands ('abandonment' trajectory, 1/3 of the total area) that are harder to access would be abandoned. This would lead to a process of secondary succession favouring taller plants with slower growth rates and corresponding changes in PFTs (decreasing LPC and increasing LDMC). As the dominance of these species increases, the variance in flowering phenology would decrease. In the 'going wild' scenario, decreasing financial support provided for mountain agriculture is projected to accelerate the current extensification trend and most of the grasslands are abandoned ('abandonment' trajectory over 2/3 of the total area) although some areas would be converted to extensive summer grazing by transhumant flocks ('grazing' trajectory over 1/3 of the total area). Conversion of hay meadows to grazing would favour unpalatable plants that have low nutrient content (low LPC) and stronger mechanical defences against herbivory (high LDMC). As the dominance by these species increases, the variance in flowering phenology would decrease.

Scenarios for Mértola

Effects of agro-pastoral abandonment on PFT and ecosystem attributes at Mértola were quantified from observations of ongoing land-use change and results are used here to translate the effect of scenarios (Castro et al., unpublished data). In the staying tame scenario, current management of the Montado understorey is projected to be maintained over the majority of the area ('no change' trajectory representing 70% of the total area), and the dense shrub cover existing on previously abandoned Montado be cleared and used for extensive livestock grazing over the remaining area ('shrub clearing for grazing' trajectory represent 30% of the total area). In the no change trajectory there would be no significant changes in either PFTs or LUAs. For the shrub clearing for grazing trajectory, there would be a decrease in LDMC and plant stature as late successional plant species decrease in abundance. Both chemical fertilization and flock size LUAs would increase as flocks return and chemical fertilizer is applied to accelerate vegetation regrowth following shrub clearing and to lengthen the grazing season. Correspondingly, LPC would increase as plants with higher relative growth rates are favored. In the going wild scenario, all agricultural activities in the Montado ecosystems would decline. Abandonment would occur over all of the site ('abandonment' trajectory). A thick shrub understorey would replace grazed or cultivated areas as indicated by an increase in plant stature and LDMC. Dominance by only a few shrub species such as *Cistus ladanifer* would decrease variance in flowering phenology.

Sensitivity

Sensitivity information is derived by sequentially applying the matrices described above to the changes in land use attributes and PFT as projected by scenario modelling (Fig. 5a). In a non-spatial scenario formulation as presented here, this is initially done per land-use change trajectory. Alternatively, it could be done per patch or pixel if changes in land-use attributes and PFTs are mapped using a spatially explicit approach to land-use change scenarios. The resulting sensitivity outcomes are then aggregated across trajectories (or across the site map) to produce a site level value. The two steps are detailed below for Lautaret only, and are illustrated in Fig. 1.

Using the framework to assess trajectory and site level sensitivity

Trajectory level sensitivity represents projected changes in ecosystem services per land-use trajectory (or in the case of a spatially explicit approach, per patch or pixel).

The series of matrix multiplications are illustrated in Fig. 2. Projected changes in plant functional traits are converted to projected changes in ecosystem attributes by multiplying the relevant data in Fig. 5a and the PFT matrix (Fig. 4c). In the same way, using the ecosystem attributes and land use attributes matrices (Fig. 4a-b), projected changes in ecosystem and land use attributes are converted into projected changes in both land use and biophysical descriptors. These are then compiled into a common table of projected changes, which is multiplied by the descriptor matrix (Fig. 3c) to give projected changes in ecosystem services (Fig. 5b).

To up scale to site-level sensitivity, a weighting is applied to results obtained for each land-use change trajectory. For the examples given here, we apply an area-based weighting, representing the proportion of area represented by each land use trajectory at the site (Fig 5a). In the Lautaret example, ecosystem service ‘sensitivity’ to the land-use trajectory ‘fertilization’ is multiplied by 2/3 while the ‘sensitivity’ to ‘conversion to grazing’ is multiplied by 1/3. Both of these are then added to provide an aggregate site level sensitivity score for each ecosystem service within each scenario (Fig 5c). Other weighing schemes are possible, for example based on accessibility of the area to stakeholders or on the number of stakeholders that rely on a given land-use trajectory (e.g. farmers on grazing land, hunters on abandoned agricultural areas). In the examples presented here, values are rescaled to the Likert scale for a qualitative assessment of the direction of change. They represent negative (-), positive (+) change, or no change (0), relative to the present day levels of delivery for the selected services.

Illustrating trajectory and site level sensitivity outcomes

To illustrate the above methodology, projected changes in ecosystem services for each land-use trajectory in Lautaret were obtained by applying the successive data transformations presented above. The trajectory level sensitivities for the two scenarios at Lautaret result in a mixed set of changes, some changes shared (for example, no change in wild beauty for fertilization and conversion to grazing), others contrasting (increase and decrease for hay for winter fodder for the fertilization and conversion to grazing trajectory, respectively). The fertilisation trajectory results in the greatest number of increases in services (2). For site level sensitivity, at Lautaret, the staying tame scenario results in two increases in services (hay for winter fodder and habitat for fauna), and a decrease in wild beauty, where in the going wild scenario wild beauty of the landscape and hay for winter fodder decrease (Fig 5c).

Acceptability

Acceptability is calculated by multiplying the ecosystem service matrix (Fig 3a) by the site level sensitivity scores for each ecosystem service under each scenario (Fig. 5c). Acceptability is rated on a three point Likert scale (- = not acceptable, 0 = neutral, + = acceptable). Scores represents the acceptability of projected changes for each ecosystem services to each stakeholder for each scenario. The calculation assumes that stakeholder preferences as indicated in the ecosystem service matrix (Fig. 3a) do not change under the scenarios (but see Acosta-Michlik et al. 2005). Acceptability and vulnerability assessments are distinguished from each other by the number of scenarios included in the assessment, where a vulnerability assessment necessarily includes all scenarios. Results for Lautaret and Mértola illustrate the type of outcome given by the framework (Figs. 6a-b respectively). Acceptability of projected changes in ecosystem services to stakeholders can be compared within a site or across sites. For example, within a site, the acceptability of ecosystem service change might be compared between farmers and hikers for a selected scenario. Across sites, the acceptability of a given scenario to farmers at different sites might be compared. The acceptability of each scenario to all stakeholders can also be compared and used to rank the acceptability of each scenario projection. An assessment of the acceptability of change to farmers for all scenarios would contribute to a vulnerability assessment (see below).

Calculating acceptability summary measures

In order to compare stakeholder or scenario acceptability, summary measures can be calculated in a range of ways. Any summary measure must first apply a weighting scheme to both stakeholders and ecosystem services (for example, the former by group membership number at each site, and the latter by counts of assigned positive values), and the acceptability values multiplied by these values accordingly. For purposes of presentation here we have assigned equal weightings to all services and stakeholders, and therefore directly calculate our summary measures from the acceptability scores (Figs. 6a-b). We present two methods of calculating summary measures here. The first represents a qualitative ranking of the acceptability of changes in the selected services by selected stakeholders (‘acceptability score’). It is calculated by summing up the acceptability scores for selected stakeholders, across ecosystem services for a given scenario (Fig. 6a, for Lautaret), and taking the sign of this value. A positive or neutral value means an overall acceptable assessment of changes, while a negative value means an overall unacceptable assessment of changes. For the purposes of this paper, we restrict this measure to a qualitative measure of the direction of acceptability only (sign), rather than including the magnitude of the direction of acceptability (leaving the values as a sum). This is formally required to maintain consistency of scales across the framework since a three point Likert scale was used for the input data, the matrices and sensitivity data.

The second method represents a more detailed quantitative measure. The 'acceptability fraction' focuses only on the services of concern, i.e. whether selected stakeholders have attributed a positive or negative value to them in the ecosystem service matrix (Fig. 3a). It is calculated by summing the counts of the number of selected positive or neutral acceptability scores (for services of concern) and representing this as a fraction of the count of selected negative scores (Figs. 6e-f). Neutral (0) acceptability scores (Fig. 5c&f) that result from a neutral evaluation of an ecosystem service (Figs.3a-b) are not included in this calculation.

This approach and the associated range of methods available to calculate acceptability summary measures enables a wide range of comparisons to be made. These comparisons can be made either within a site, between scenarios, or between sites for a given scenario, in terms of a single ecosystem service, a subset, or the full set of, ecosystem services, by a single stakeholder, a subset of, or by all stakeholders. It is important to note that these two methods calculate different things and can result in different assessments of comparative acceptability. Each score and associated assessment therefore must be interpreted in terms of the context of the assessment objectives. As an example, we present and briefly discuss a comparison between local farmers at Lautaret and local farmers and farm owners at Mértola for the staying tame scenario.

Illustrating acceptability outcomes

At both sites, the acceptability score for farmers for the staying tame scenario is the same (+, Figs. 6c-d). This means that farmers at both sites would evaluate the acceptability of the staying tame scenario in relation to its impacts on all services considered together similarly.

Farmers at both sites also share a similar acceptability fraction (2/0), meaning that they would evaluate the relative acceptability versus non-acceptability to the changes in the ecosystem services of the staying tame scenario similarly (Figs. 6e-f). At both sites, farmers would find the changes in ecosystem services twice as acceptable than unacceptable. A closer examination of the matrices for the two sites reveals that these similar acceptability scores arise from different values being assigned to different services (Figs. 3a-b) and differences in the associated sensitivity values at each site (Figs. 5c&f). For example, contrasting values are placed on the cultural services, where farmers at Lautaret assigned a negative value to 'wild beauty of the landscape' in contrast to farmers at Mértola who placed a positive value on 'agro-pastoral scenic value'. Farmers at Lautaret assigned a negative value to 'wild beauty' as they perceived this representation as an antithesis to their own 'domestication' representation of the landscape where farmers are the stewards (Quétier et al., submitted a). The sensitivity tables for the two sites (Figs. 5c&f) show that all the projected changes in services for the staying tame scenario differ across sites. However, when these scores are multiplied with the respective ecosystem service matrix, a similar acceptability score results. For example a negative value assigned to wild beauty combined with a decrease in the ecosystem service delivery results in a positive acceptability for farmers at Lautaret, where at Mértola a positive value assigned to agro-pastoral scenic value, combined with an increase in the ecosystem service delivery also results in a positive acceptability.

Vulnerability assessment

Vulnerability is calculated in the same way as comparative acceptability but always involves the full set of scenarios to take into account the full range of measured exposure. Comparisons can be made within site, comparing stakeholders or sets of stakeholders, as well as across sites. Where the vulnerability of a selected set of stakeholders in relation to another set is compared, as is the case for our approach, it is important to note that vulnerability assessment, like comparative acceptability is always relative, never absolute. The framework enables a wide range of vulnerability assessments to be made, as discussed above for comparative acceptability. We present and briefly discuss two examples of vulnerability assessment.

Illustrating vulnerability assessment outcomes: comparing farmers and the National Park Authority at Lautaret

The acceptability score for farmers is +, and 0 for the National Park Authority (Fig. 6c). This calculation suggests that when considering an overall ranking of acceptability to changes in all services, the National Park Authority is more vulnerable to projected changes in ecosystem services than farmers. For the acceptability fraction, farmers have a value of 3/1, while National Parks Authority have a value of 3/3. This calculation suggests, similar to the acceptability score, that in terms of comparing acceptability over non-acceptability, the National Park Authority is more vulnerable than farmers. Farmers overall, would evaluate three times more acceptable than unacceptable changes in the ecosystem services.

By exploring the successive tables obtained from applying the proposed framework, several reasons for these differences can be found (and subsequently tested if necessary – see discussion). The National Park Authority assigned a positive value to the wild beauty of the landscape whereas farmers valued this ecosystem service negatively. As it decreased in both scenarios, the NPA was negatively affected whilst farmers were positively affected (Figure 6a). This explains why the NPA is most vulnerable. However, further exploration of acceptability results also shows that the difference between the two stakeholders would have been even greater if farmers had valued habitat for fauna positively, as the NPA did (Figure 3a). This ecosystem service increased under both scenarios and while the NPA benefited from this effect, farmers remained neutral (Figure 6a).

Illustrating vulnerability assessment outcomes: comparing Lautaret and Mértola for all stakeholders

Collectively, the acceptability score for stakeholders at Lautaret and at Mértola is the same (0, Figures. 6c-d). This suggests that in terms of an overall ranking of acceptability relative to all services, stakeholders at Lautaret and Mértola are similarly vulnerable. Comparing scenarios across sites, the acceptability scores are also shared (staying tame =+ and for going wild = -), and balance each other out. Acceptability scores however differ for stakeholders. For Lautaret for the going wild scenario, farmers have a relatively higher acceptability score (0) than farmer at Mértola (-), and hikers have relatively lower acceptability score than hunters at Mértola (- and + respectively). Tracing these scores back to the assigned ecosystem service preferences (Figures. 3a-b) and the changes in these services under this scenario (Figures. 5c&f), reveals that, for example, farmers assigned a negative value to wild beauty and hikers assigned a positive value, with this service decreasing under this scenario (see above for comparing stakeholders within a site).

An assessment based on acceptability fractions, and hence ecosystem services of concern to each stakeholder, indicates that both sites are similarly placed in terms of comparing relative acceptability over non-acceptability (Figs. 6e-f). For the acceptability fraction, Lautaret has a value of 6/6 while Mértola has a value of 5/5. At Mértola, all three stakeholders have the same relative numbers of acceptable versus not acceptable scores. At Lautaret, all stakeholders differ in their fractions, with hikers having the lowest acceptability to non-acceptability fraction (0/2) and farmers having the highest (3/1).

Discussion

The framework, illustrated with some simple examples of comparative acceptability and vulnerability assessment, represents progress towards an integrated approach and methodology for vulnerability assessment in a number of ways. We discuss three key contributions below, demonstrating how the framework contributes towards better involving social values in the assessment process, and what aspects of the framework contribute to a quantitative and a transparent means to do so.

Integrating the social dimension of vulnerability

The use of social surveys to both identify and value ecosystem services and associated descriptors provides the practical means to accommodate social values in the framework. Our approach, like several others (e.g. Lewan and Söderqvist 2002; Kaplowitz 2001; Shanley and Luz 2003; Rodriquez et al. 2005) puts these steps of identification and valuation of ecosystem services explicitly into the social realm. Our approach to vulnerability is also comparative, where given different groups of stakeholders, possibly holding different views of what are considered important ecosystem services and how they might value these, a range of evaluations of vulnerability may occur. We see this comparative approach as an important feature of our framework, emphasising the importance of how (multiple and differing) social values determine evaluations of ecosystem change.

Many recent studies involving valuation and assessments of ecosystem services do not take this social aspect to the identification and valuation of ecosystem services into account. Typically, studies undertake these steps exclusively as part of the biophysical assessment (e.g. Balvanera et al. 2005; Díaz et al. 2005; Hooper et al. 2005, Townsend et al. 2003, and many others). However, a small (and increasing) number of studies do include a social valuation step, even though ecosystem service identification remains *a priori*, usually undertaken by biophysical scientists (Bolund and Hunhammar 1999; Holmlund and Hammer 1999; Gitay et al. 2001; Daily 1997, de Groot et al. 2002). By including ecosystem services identified by stakeholders, and having stakeholder values determine the valuation process, the proposed framework sets itself apart from the majority of these exercises.

The use of descriptors identified by stakeholders to link ecosystem services to relevant underlying ecological attributes (Table 2a-b) also represents progress towards better incorporation of social values into the assessment process. Many existing ecosystem service classifications (e.g. de Groot et al. 2002, Millennium Ecosystem Assessment 2005) include abstract or intangible ecosystem services such as inspirational or existence value, or sense of place. These types of services are proving less easy to practically quantify and measure, as these classifications provide little guidance for how to link such services to relevant ecosystem attributes (Roderíquez et al. 2005; de Groot and Ramakrishnan 2005). Here, the inclusion of stakeholder descriptors, for example variety of flower colours, visual cues of present agricultural activities, and open landscape to link to the wild beauty of the landscape at Lautaret makes the incorporation of these types of ecosystem services more tractable. In some circumstances developing links from services to descriptors may be difficult, as when stakeholders assign a global positive value to a service with little explicit links to finer resolution features. This can for instance be the case when urban dwellers value biodiversity generically, but do not relate this appreciation to particular groups of organisms, taxa, or even less specific ecosystem elements (Johansson and Lindström 2003; Plateryd 2003).

For those ecosystem services that have a more obvious link to physical elements of ecosystems, such as many of the ‘provisioning’ (e.g. food and fibre production, genetic resources) or ‘regulating’ services (e.g. erosion control, pollination) (Millennium Ecosystem Assessment 2003; 2005), some ecosystem attributes or plant functional traits can be used as both descriptors and underlying ecological processes. This makes the inclusion of descriptors not only qualitatively but also quantitatively more efficient (Lavorel and Garnier 2002). Rangeland management for example, relies increasingly on PFTs to describe the agronomic quality of resources available for grazing (Díaz et al. 2002; Ansquer et al. 2004).

As presently formulated in the framework, all stakeholders share a common descriptor matrix (Table 4). However this assumed shared perspective on what constitutes a descriptor and how it is valued might not always be appropriate. For example, at Lautaret although farmers and hikers appeared to share a common perspective on what is considered ‘wild beauty’ of the landscape, farmers tended to have a greater technical knowledge of grasslands. In the individual interviews, farmers provided more quantified and technically based descriptors in contrast to hikers. For situations such as this, a set of stakeholder specific descriptor matrices could be substituted for the shared descriptor matrix. Descriptors that are unique to a stakeholder type for a given ecosystem service (such as descriptions of agronomic value as provided by farmers at Lautaret) and/or how a descriptor might be uniquely valued can then be accommodated.

Calculating acceptability using the ecosystem service matrix has several limitations. The first limitation is that the calculated acceptability is based on stakeholders’ valuations of ecosystem services for the present day. This valuation is likely to change as the economic, social and cultural context of valuation changes in the future. A second limitation is that acceptability does not accommodate other adaptation strategies included in the definition of adaptive capacity given in the introduction. These other strategies might include mitigation, where a change in stakeholder management strategies feed back to change exposure (e.g. modifying land use change projections set by the scenarios), and/or a change in the stakeholder population itself such as emigration or immigration (Acosta-Milchik et al. 2005).

However, with the inclusion of additional social survey techniques, the framework can serve as a basis for more direct means of assessing acceptability. For example, a second round of stakeholder interviews to illustrate scenario outcomes using narratives has been undertaken at Lautaret. A range of tools such as digitally modified photographs, artists’ impressions, maps representing changes in ecosystem services, short stories are available for this (e.g. Hunziker 1995). This has allowed for a range of decision-making strategies to be accommodated in relation to how stakeholders assign acceptability to scenarios. Public discussion techniques (Farber, Costanza and Wilson 2002) could also be included to provide a forum for stakeholders to exchange their views on scenario acceptability. Several advantages of these methods are that participating individuals can seek wider input from others to form a personal judgement, or participate in forming a shared community judgement, if this is appropriate.

Flexibility in methods for classifying and linking ecological and social data

The matrices provide the platform for quantification and integration of social and ecological information. They provide a transparent and flexible means for both classifying information (changing and/or weighting rows and columns) and describing their links. Here, we used a three point Likert scale for a simplified presentation, but more sophisticated (qualitative as well as quantitative) measures could be substituted. For example, an extended Likert rating scale could be used to incorporate magnitude as well as direction of change in selected variables. Continuous variables could be used such as the marginal economic value of ecosystem services, or quantitative changes in projected ecosystem attributes. Provided that corresponding methods can be developed for table multiplication, complex relationships incorporating thresholds could also be used.

The ecosystem service matrix (Figure 3a-b) can accommodate a full range of ecosystem services and stakeholders. As discussed above, the matrix format allows stakeholders to share or have unique sets of ecosystem services and descriptors (Figure 3a-d), and to assign shared or different values to these. Assessments can be made using multiple values for a given ecosystem service, incorporating the necessarily plural nature of ecosystem valuation.

We assigned equal weights to all ecosystem services and to stakeholders for the examples presented here. However, given a particular setting for vulnerability assessment, it may be appropriate that local residents' opinions are considered to be more important than non-residents', or that stakeholder types with a large membership be considered more important. The proposed matrix approach can accommodate differential weighting of stakeholders and/or ecosystem services, though decision making approaches for assigning these weightings is an area of research outside the scope of this paper. This possibility is an important feature of the framework as it is commonly assumed in valuation studies that individual preferences are equivalent. Instead, it may be more appropriate to weight opinions according to some criteria such as education, expert knowledge, or residence status (Goulder and Kennedy 1997).

Given relevant data and established relationships between matrix variables, the framework could be used to test whether any additions or simplifications to the matrices might improve the links between social and ecological data. For example, one limitation of the three point rating scale used here is that it may mask the consequences of the diversity of individual views on ecosystem services within a stakeholder type, or of the context-dependent strength in relationships between plant functional traits and ecosystem attributes. Given more quantitative relationships, the impact of the loss of information resulting from the use of a minimal rating scale could be evaluated.

In addition, the matrix format provides many possibilities for adding, substituting or removing relationships between data types. We illustrated the framework using an initial PFT matrix (Figure 4c) as a general tool for modeling land-use change effects on ecosystems. However, other avenues are possible for obtaining relevant changes in ecosystem properties underlying ecosystem service provision. Substituting the PFT matrix or the EA matrix with an appropriate alternative is made easy by the matrix format on which the framework is based.

Analysing underlying causes of vulnerability across stakeholders and ecosystem services in contrasting settings

The transparent and deterministic nature of the matrices enable a range of vulnerability comparisons to be made, in a variety of different situations and regions. Different assessments can be compared and discussed in parallel. As illustrated by our example of vulnerability assessment between Mértola and Lautaret, the framework can make assessments in regions with different ecological and social-economic contexts, comprising different stakeholders who value different ecosystem services differently.

The framework also allows for an examination of the ecological and social factors that contribute to the overall assessment of vulnerability. For example, plant traits, which are a key element of the proposed assessment methodology, are a widely applicable approach for describing processes that drive ecosystem change (Westoby et al. 2002; Díaz et al. 2004; Wright et al., 2004; Lavorel et al., 2005). Using them to link projected changes in vegetation to ecosystem processes using the PFT matrix (Figure 4b) contributes to the wide applicability of the proposed framework, while also making the underlying mechanisms explicit. As the understanding of these relationships and mechanisms gets refined, so could quantification of changes in ecosystem services, hence improving vulnerability assessments. The matrix format also makes it possible to highlight ecological trade-offs – represented by PFT-PFT and PFT-EA relationships - that may impose hard boundaries on the delivery of multiple services by a given ecosystem.

The matrix format is also particularly appropriate to analyse conflicts between stakeholders or resulting trade-offs among ecosystem services. Farmers at Metola and Lautaret had equal acceptability for the staying tame scenario, however they disagreed on how they value ecosystem services (Figure 3a-b). The matrix approach makes each step of the analysis tractable, revealing the pluralistic nature of acceptability. For example, it allows an examination of which scenarios each group of stakeholders is likely to find more acceptable or otherwise (Figure 6c-f) and why (Figure 6a-b).

The capacity of stakeholders to discuss and resolve value conflicts is an important component of adaptive capacity. Our use of acceptability as a measure of adaptive capacity does not provide information on this type of capacity for conflict resolution. Other proposed measures of adaptive capacity propose using socio-economic indicators such as GDP, education level or literacy as proxies for such capacity (e.g. Schröter et al. 2003). However they do not include a means of making conflicts between stakeholder types explicit. The matrix format provided by our framework provides the means for identifying these conflicts and thereby possibly act as a first step in overcoming them.

These types of comparisons and examinations about the nature of vulnerability have been identified as an important input into the environmental decision making and policy arena (Rodriquez et al. 2005). The proposed framework provides a flexible means of making this possible in a generally applicable and transparent way, by linking the ecological characteristics of the environment and the social, cultural or economic information on why and how it is valued.

Acknowledgements

This research was carried out as part of the EU funded project VISTA (Vulnerability of Ecosystem Services to Land-use Change in Traditional Agricultural Landscapes - EVK2-2001-000356). We also thank two anonymous reviewers and two editors for their constructive comments on the manuscript.

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Appendix 1

Plant functional traits (PFT hereafter) are the morphological, ecophysiological, biochemical or regeneration characters that determine the response of plant populations to changes in the environment and/or their effects on ecosystem functions such as biogeochemical cycling, propensity to burn or be grazed, or stability in the face of disturbance (Gitay and Noble 1997, Lavorel and Garnier 2002).

Ecosystem attributes are structural or functional characteristics of ecosystems. They include plant functional traits such as plant height or specific leaf area, other structural properties such as species richness or vegetation structural diversity, and processes such as aboveground net primary production or litter decomposition.

Land-use attributes are descriptions of management practices (including intensity of management) that characterise the land-use(s) for a given ecosystem. Examples include organic fertiliser input, presence of features of agricultural activity (fences, irrigation equipment), grazing intensity or hay cutting. They represent the interplay between the biophysical constraints of the local region and the various land-use drivers (social, economic, technological) that influence the region. They play an important role in determining ecosystem attributes through the modification of resources and disturbance regimes.

Stakeholders are individuals, a set of individuals, and/or a community or an agency with identified preferences for a single, or set of ecosystem services.

Ecosystem services are defined as 'the benefits people obtain from ecosystems' (Millennium Ecosystem Assessment 2003, p 3). They include 'provisioning services such as food and water; regulating services such as regulation of floods, drought, land degradation, and disease; supporting services such as soil formation and nutrient cycling; and cultural services such as recreational, spiritual, religious and other nonmaterial benefits such as spiritual or aesthetic benefits'(Millennium Ecosystem Assessment 2003, p 3).

Descriptors are stakeholder derived descriptions of observable characteristics of ecosystems. Descriptors include 'natural' or less human modified elements such as trees, wildflowers, and wild animals through to more human modified elements such as fences, farm machinery, and livestock. Descriptors are linked to either ecological attributes or land-use attributes. Descriptors linked to the ecosystem attributes are termed biophysical descriptors. Descriptors linked to land-use attributes are termed land-use descriptors. We note that there is sometimes overlap between the two groups of descriptors where a descriptor may be linked to both an ecosystem attribute and a land-use descriptor. A descriptor may also be the same as an ecological or a land-use attribute.

Scenarios are plausible and often simplified descriptions of how a future may develop, based on a coherent and internally consistent set of assumptions about driving forces and key relationships. Scenarios may be derived from simulation model projections, but are often based on or supplemented by additional information, sometimes combined with a 'narrative storyline' (McCarthy et al. 2001; Millennium Ecosystem Assessment 2005).

Figures

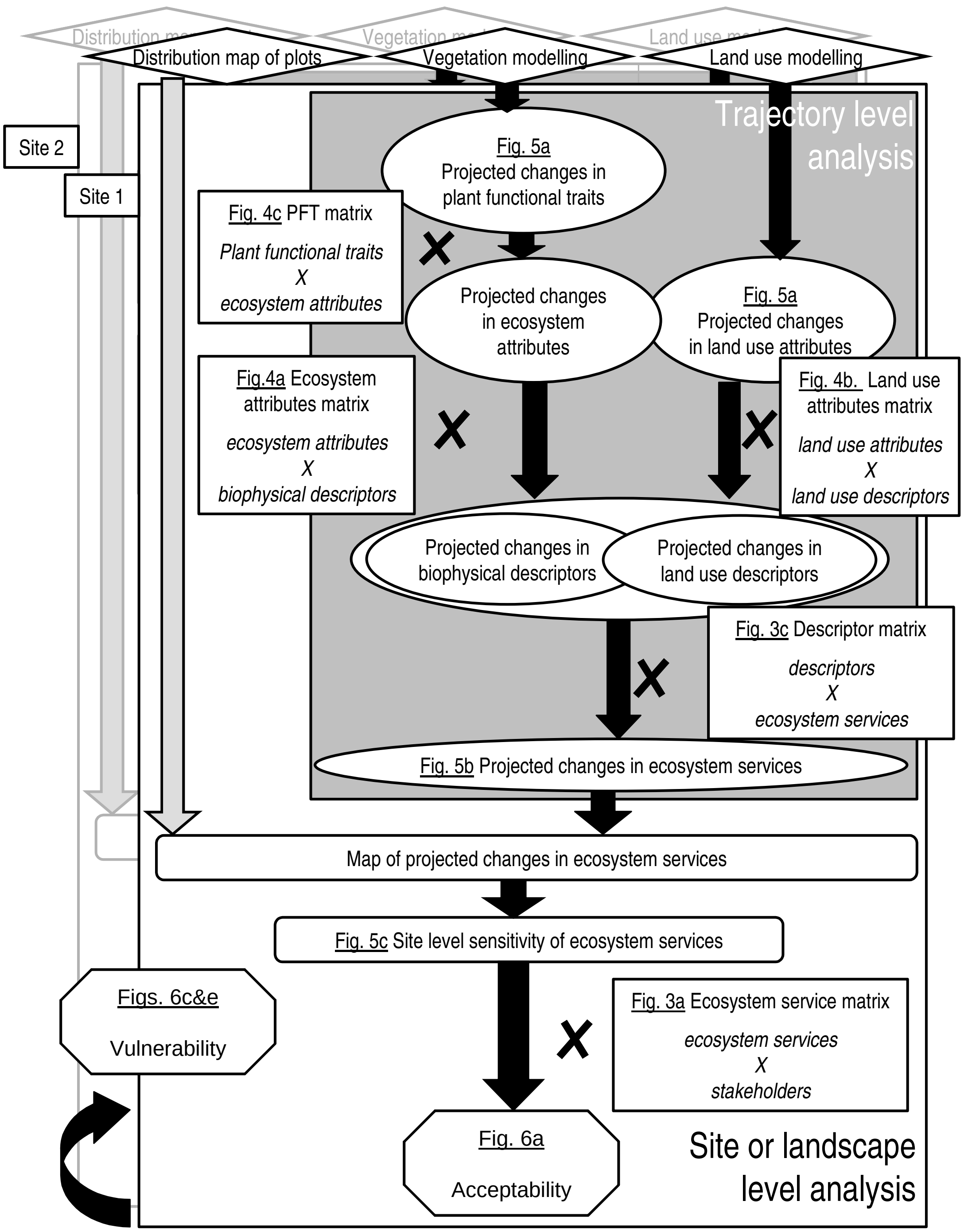

Figure 1

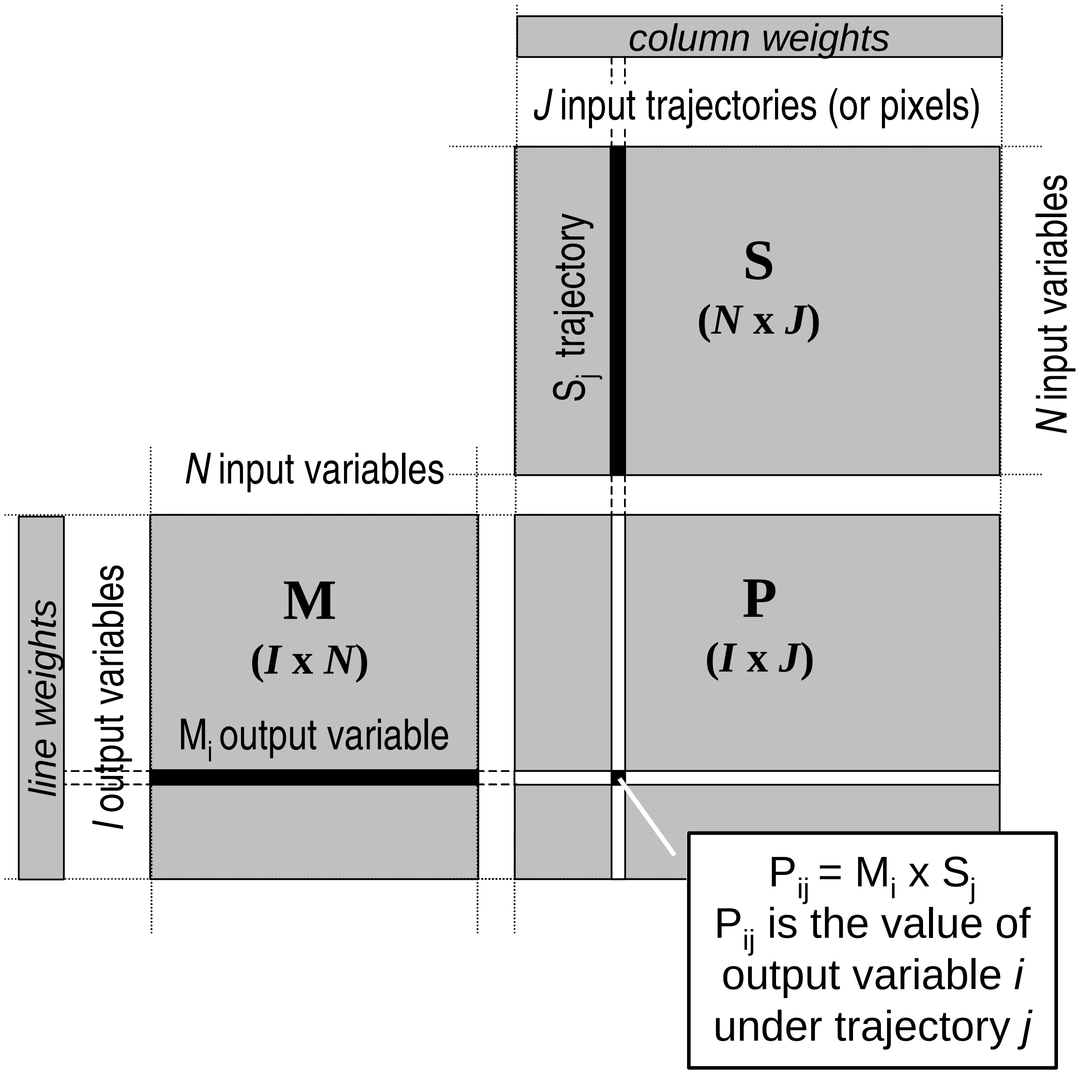
column weights
J input trajectories (or pixels)
S
(N x J)
S_j trajectory
N input variables
N input variables
line weights
I output variables
M
(I x N)
M_i output variable
P
(I x J)
P_ij = M_i x S_j
P_ij is the value of
output variable i
under trajectory j

Figure 2.

Ecosystem Service matrix (Col du Lautaret)		Ecosystem Services		
		Wild beauty of the landscape	Hay for winter fodder	Habitat for fauna
Stakeholders	Hiker	+	0	0
	Farmer	-	+	0
	National Park Authority	+	+	+

a.

Ecosystem Service matrix (Mertola)		Ecosystem Services		
		Agro-pastoral scenic value	Honey production	Abundance of game
Stakeholders	Hunters	0	0	+
	Farmers	+	+	0
	Natural Park Authority	+	0	-

b.

Descriptor matrix		Stakeholder descriptors					
		Variety of flower colours	Grassland productivity	Abundance of legumes	Abundance of unpalatable plants	Visual cues of agricultural activities	Open landscape
Ecosystem Services	Wild beauty of the landscape	+	0	0	0	-	+
	Hay for winter fodder	0	+	+	-	+	+
	Habitat for fauna	0	+	0	0	-	-

c.

Descriptor matrix		Stakeholder descriptors		
		Abundance of flowers	Shrub density	Presence of grazing livestock
Ecosystem Services	Agro-pastoral scenic value	+	-	+
	Honey production	+	0	0
	Abundance of game	0	+	-

d.

Figure 3a-d.

Ecosystem Attribute matrix (Col du Lautaret)		Ecosystem Attributes			
		Phosphorus availability for plant growth	Flowering Diversity Index	Grass productivity (Kg.m^{-2})	Abundance of *Festuca paniculata* (%)
Stakeholder Descriptors	Variety of flower colours	0	+	0	-
	Grassland productivity	+	0	+	0
	Abundance of legumes	+	0	0	-
	Abundance of unpalatable plants	-	0	0	+

a.

Land Use Attribute matrix (Col du Lautaret)		Land-use Attributes	
		Organic Fertilization	Flock size
Stakeholder descriptors	Visual cues of agricultural activities	+	+
	Open landscape	0	+

b.

PFT matrix		PFTs			
		Plant Stature	LDMC	LPC	Variance in flowering phenology
Ecosystem Attributes	Phosphorus availability for plant growth	+	-	+	0
	Flowering Diversity Index	0	0	0	+
	Grass productivity (Kg.m^{-2})	0	-	+	0
	Abundance of *Festuca paniculata* (%)	+	+	-	0

c.

Figure 4a-c.

Scenario based input (Col du Lautaret)		Land-Use Trajectory		
		Fertilization	Conversion to grazing	Abandonment
Scenario (share of area affected)	*Staying Tame*	2/3	0	1/3
	Going Wild	0	1/3	2/3
PFTs	Plant Stature	+	0	+
	LDMC	-	+	+
	LPC	+	-	-
	Variance in flowering phenology	+	-	-
Land Use Attributes	Organic Fertilization	+	-	-
	Flock size	-	+	-

a.

Matrix manipulation

Trajectory level sensitivity	Land-Use Change Trajectory		
	Fertilization	Conversion to grazing	Abandonment
Wild beauty of the landscape	0	0	-
Hay for winter fodder	+	-	-
Habitat for fauna	+	-	+

b.

Site level sensitivity		Scenarios	
		Staying Tame	*Going Wild*
Ecosystem services	Wild beauty of the landscape	-	-
	Hay for winter fodder	+	-
	Habitat for fauna	+	+

c.

Scenario based input (Mertola)		Land-Use Trajectory		
		No change	Shrub clearing for grazing	Abandonment
Scenario (share of area affected)	*Staying Tame*	2/3	1/3	0
	Going Wild	0	0	3/3
PFTs	Plant Stature	0	-	+
	LDMC	0	-	+
	LPC	0	+	-
	Variance in flowering phenology	0	0	-
Land Use Attributes	Organic Fertilization	0	+	-
	Flock size	0	+	-

d.

Matrix manipulation

Trajectory level sensitivity	Land-Use Change Trajectory		
	No change	Shrub clearing for grazing	Abandonment
Agro-pastoral scenic value	+	+	-
Honey production	0	0	-
Abundance of game	-	-	+

e.

Site level sensitivity		Scenarios	
		Staying Tame	*Going Wild*
Ecosystem services	Agro-pastoral scenic value	+	-
	Honey production	0	-
	Abundance of game	-	+

f.

Figure 5a-f

Acceptability (Col du Lautaret)	Scenarios	
	Staying Tame	*Going Wild*
Hikers		
Wild beauty of the landscape	-	-
Hay for winter fodder	0	0
Habitat for fauna	0	0
Farmers		
Wild beauty of the landscape	+	+
Hay for winter fodder	+	-
Habitat for fauna	0	0
National Park Authority		
Wild beauty of the landscape	-	-
Hay for winter fodder	+	-
Habitat for fauna	+	+

a.

Acceptability (Mertola)	Scenarios	
	Staying Tame	*Going Wild*
Hunters		
Agro-pastoral scenic value	0	0
Honey production	0	0
Abundance of game	-	+
Farmers		
Agro-pastoral scenic value	+	-
Honey production	0	-
Abundance of game	0	0
Natural Park Authority		
Agro-pastoral scenic value	+	-
Honey production	0	0
Abundance of game	+	-

b.

Acceptability score	Scenarios		*Across Scenarios*
	Staying Tame	*Going Wild*	
Hiker	-	-	-
Farmer	+	0	+
National Park Authority	+	-	0
All stakeholders	+	-	0

c.

Acceptability score	Scenarios		*Across Scenarios*
	Staying Tame	*Going Wild*	
Hunters	-	+	0
Farmers	+	-	0
Natural Park Authority	+	-	0
All stakeholders	+	-	0

d.

Acceptability Fraction	Scenarios		*Across Scenarios*
	Staying Tame	*Going Wild*	
Visitor/Hiker	0/1	0/1	0/2
Farmer	2/0	1/1	3/1
National Park Authority	2/1	1/2	3/3
Across all stakeholders	4/2	2/4	6/6

e.

Acceptability Fraction	Scenarios		*Across Scenarios*
	Staying Tame	*Going Wild*	
Hunters	0/1	1/0	1/1
Farmers	2/0	0/2	2/2
Natural Park Authority	2/0	0/2	2/2
Across all stakeholders	4/1	1/4	5/5

f.

Figure 6a-f.

Figure Legends

Figure 1. Diagram illustrating the overall structure and flow of information in the framework. A comparison between two sites is illustrated here to show vulnerability, however a range of other comparisons (for example, between stakeholder types within a site) are also possible. Table labels refer to information presented for Col du Lautaret. Diamonds represent modelling input data. Rectangles represent the 5 matrices. Ovals represent projected changes at the trajectory level. Rounded rectangles represent projected changes at the site level. Octagons represent acceptability and vulnerability calculations.

Figure 2. Schematic illustration of matrix manipulations in the proposed conceptual framework. Input data (input variables per trajectory or pixel – table S) are converted into output data (output variables per trajectory or pixel – table P) using a translation matrix linking input and output variables (matrix M). Lines and columns of both the input table and the translation matrix can be weighed by introducing weight vector matrices into the matrix multiplication. As an example, 'N' input variables might represent change in ecosystem attributes (EAs) under a particular trajectory, Matrix 'M' might represent the Ecosystem Attribute Matrix, and Table 'P' represent change in descriptors under the same trajectory.

Figure 3a-d. a Ecosystem Service Matrix for Lautaret. b. Ecosystem Service Matrix for Mértola. c. Descriptors matrix for Lautaret. d. Descriptors matrix for Mértola.

Figure 4a-c a Ecosystem attributes matrix for Lautaret. b. Land use attribute for Lautaret. c. Plant Functional Trait Matrix for Lautaret.

Figure 5a-f. a Land-use attribute and plant functional trait data obtained from scenario based modelling of land-use and land-cover change for Lautaret. The proportion of total area changed at each site for each trajectory is given at the top of the table. b. Trajectory level sensitivity for each scenario for Lautaret. c. Site level sensitivity for the selected scenarios for Lautaret. d. Land-use attribute and plant functional trait data obtained from scenario based modelling of land-use and land-cover change for Mértola. e. Trajectory level sensitivity for each scenario for Mértola. f. Site level sensitivity for the selected scenarios for Mértola.

Figure 6a-f. a. Acceptability of changes in ecosystem services for stakeholders for both scenarios for Lautaret. b. Acceptability of changes in ecosystem services for stakeholders for both scenarios for Mértola. c. Acceptability scores for stakeholders for Lautaret. d. Acceptability scores for stakeholders at Mértola. e. Acceptability fractions for stakeholders for Lautaret. f. Acceptability fractions for stakeholders at Mértola.