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REVIEW ARTICLE

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Multifunctional natural forest silviculture economics revised: Challenges in meeting landowners' and society's wants: A review

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Abstract

Aim of study: This paper objective focuses on the contribution of multifunctional natural forest silviculture, incorporating both private and public product managements, to forest and woodland economics.

Area of study: Spain and California (USA)

Material and methods: This conceptual article has developed a critical revision of the existing literature on the main economic issues for the multifunctional natural forest silviculture in the last decades.

Main results: Multifunctional natural silviculture has secular roots as a local practice, but as a science of the natural environment applied to the economic management of forest lands it is still in the process of maturation. Timber silviculture remains the central concern of forest economics investment in scientific publications. By contrast, silvicultural modeling of the natural growth of firewood, browse and other non-timber forest products from trees and shrubs receives scant attention in scientific journals. Even rarer are publications on multifunctional natural silviculture for forest and woodland managements, including environmental services geared to people's active and passive consumption. Under this umbrella, private environmental self-consumption is represented by the amenities enjoyed by private non-industrial landowners. As for environmental public products, the most relevant are carbon, water, mushrooms, recreation, landscape and threatened biodiversity.

Research highlights: This paper is a good example for the conceptual research on forestry techniques and economic concepts applied to multifunctional silviculture in Mediterranean areas of Spain and California. The combination of technical knowledge and private and public economic behaviors definitively contributes to the multifunctional management of natural forest systems.

Abbreviations used: AAS (Agroforestry Accounting System); EAF (Economic Account for Forestry); ES (Ecosystem Services); GP (Goal Programming); IHRMP (Integrated Hardwood Range Management Program); MCDM (Multiple-Criteria Decision-Making); NTFP (Non Timber Forest Products).

Additional keywords: silvicultural modeling; multiple use; ecosystem accounting; multi-criteria analysis; environmental valuation; commercial auto-consumption; private amenity.

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Introduction

Multifunctional forestry has secular roots as a local practice, but as a science of the natural environment applied to the economic management of forest lands it is still in the process of maturation (Gregory, 1955; Merlo *et al*., 1987; Serrada *et al*., 2008). Forestry timber production remains the central concern of forest economics in scientific publications. By contrast, silvicultural modeling of the natural growth of firewood, browse and other non-timber forest products from trees and shrubs is under-represented in scientific publications. Even rarer are publications on the multifunctional management of forests and woodlands, including environmental services that satisfy human active and passive consumption.

Native species exhibit a high range of genetic variation linked to their natural environment, and are generally characterized by the natural growth of their harvested products, which depends primarily on environmental conditions. This production function feature of forest ecosystems makes their products less competitive in the market than private commercial substitutes produced using new technologies. The decline in the commercial production of raw materials provided by forest ecosystems with low or no biotech investment favors changes in the composition and relative weight of silviculture products which involve low or no technological intensity.

These changes in demand have been shaped by market products (private consumption) and public products (open access harvested products, water, carbon, recreation, landscape, threatened biodiversity). Given the increasing demand for the consumption of public products, the market reacts by internalizing new products (mushrooms, hunting) and the government by increasing public spending on forestry activities that prevent the degradation and/or enhance the supply of public products. We are thus faced with the challenge of reconciling the private and public multi-functionality of forest ecosystems with the wants of consumers, investors and governments.

By silviculture economics, we mean forest ecosystems comprised by wild plants and animal management that aim to satisfy current and future human consumption. Management here refers to all human action on wild plants and animals that is geared to product consumption and/or gross capital formation of environmental assets in the forest ecosystem.

The objective of this article is to review the status of published research on silviculture geared to multifunctional forest management, giving special attention to the Mediterranean hardwoods in Spain and California. In the absence of threatened wildlife species and forest habitats, forestry is a subsidiary of current human demands, with the government acting as the representative of the whole of society in its role as the depositary for meeting the expected demands of future generations. A second objective of this study is to review the literature on multifunctional forest economics, focusing on economic rationality in terms of the efficiency, profitability and tolerable social cost of forest ecosystem management.

Our analysis here does not include forest plantation and game management, in which the control of the natural environment significantly reduces the range of expected variation of a product's bio-physical productivity over the production cycle. In other words, we will not deal here with cultivated forests or highly controlled game farming.

We will provide a qualitative description of concepts, methods and models of forest ecosystem silviculture, illustrating these, generally, with published references.

Silviculture natural growth models and yield cycles of forest stands

Timber production has traditionally been the main objective of forest management. Although other products have always been enjoyed by society, they were not formally recognized as forest management practices, which focused almost exclusively on obtaining timber. The concept of mutifunctionality that arose in the last century (Dieterich, 1953) obliged forest managers to embrace different management objectives. Silvicultural schedules started to become more oriented to obtaining different products from forest stands, namely non-timber forest products, including public products as carbon sequestration and recreational values. In order to develop multifunctional silvicultural schedules, it is essential to have growth and yield models available that allow us to predict the effect of silvicultural operations on stand development as well as expected products. Although multifunctional product consumption from Mediterranean forest stands is evident, multifunctionality has until now barely been considered in any quantitative way since there is no accurate available data that could allow us to quantify the different products. Take, for instance, the case of *Quercus ilex*. The characteristics of this species of providing firewood, as well as food for wild game and livestock, are widely acknowledged, but we do not have as of yet any robust models that allow us to predict acorn production depending on stand or climate-related variables. Recently some attempts have been made in this direction and the first steps for assessing this type of model have been taken (Montero *et al*., 2015).

The reason for the lack of models may be two-fold. In the first place, keeping track of grazed production in these stands is expensive in terms of both the time and monetary costs for research institutions, even when there is a well-established market for grazed fodder, as is the case of acorns for fattening Iberian pigs in the *montanera* season. In contrast to the *Q. ilex* are the cases of *Quercus suber* and *Pinus pinea,* in which demand for the cork and nuts, respectively, that are obtained from these species has triggered the development of very robust and detailed models for predicting both the growth and yield of these stands (Montero, 1987; Sánchez-González *et al*., 2008; Calama *et al*., 2011). Both species present similar characteristics in terms of management complexity. In the case of *Q. suber*, the existence of several debarking cycles combined with uneven production throughout the tree's life makes managing this species a challenging task. In the case of the *P. pinea*, the mating habit that characterizes this species was the main challenge that needed to be overcome. Nevertheless in both cases silvicultural schedules have been successfully developed, optimizing both the physical production of these stands (Montero *et al*., 2015) and their economic profitability (Pasalodos-Tato *et al*., 2016).

Developing growth and yield models makes it moreover possible to develop other types of silvicultural schedules, such as, for example, the so-called "silviculture of carbon" (Ruiz-Peinado & Montero, 2009). This type of silviculture schedule provides guidelines for forest managers, allowing them to orient management to maximizing the carbon sequestered in stands. Examples of these types of guidelines are extending rotation lengths (Sohngen & Mendelsohn, 2003; Kaipanen *et al*., 2004) or intensifying thinning programs (Jandl *et al*., 2007), silvicultural practices that are recommended particularly in stands with low productivity. As in the former cases we described, growth and yield models also play a relevant role here, in this case predicting the amount of carbon that a stand is capable of sequestering.

Modeling natural growth and capture cycles of forest wild game species

Recreational hunting has gained importance for grazing economics in forest and woodland areas that have been abandoned by livestock grazing in Spain and other countries. This situation has made managing game species an object of increasing attention in grazing economics (Milner *et al*., 2006; Apollonio *et al*., 2010; Herruzo & Martínez-Jauregui, 2013). Within this context, modeling wild game species rearing is essential in order to gather information about natural growth and game capture cycles. In a steady state situation (long-term sustainable yield) the environmental value of the animals captured (used work in progress) - when the latter includes game stock period revaluation - should equal the value of natural growth (permanent environmental income). This has been found to be the case in large areas in Spain (Herruzo *et al*., 2016).

The modeling of natural growth and captures has been explored recently in Spain by Herruzo *et al*. (2016), with a view to incorporating recreational hunting into standard and extended national accounts (Campos, 2000, 2015a; EC, 2000; Campos *et al*., 2008). In the research conducted by Herruzo *et al*. (2016), the natural growth of settled species was measured by environmental gross work-in-progress formation (total births and revaluation of animals whose main economic function is not reproductive) and gross fixed capital formation (revaluation of females whose main economic function is reproductive). The revaluation of animals is represented by the variation in their value at the closing period with respect to that at the opening period. Population dynamics in a steady state and environmental prices were used to calculate these values. Population dynamics that maintain a stable population were defined using a deterministic matrix model structured by sex and age and assuming a known initial population, along with previously known capture, longevity, fertility, and mortality rates (Carranza *et al*., 2015). Environmental prices were estimated using the residual valuation method based on hunting lease prices (Martínez-Jauregui *et al*., 2016a). Finally, natural growth of migrant species was valued at hunting market prices (Herruzo *et al*., 2016).

Further research needed to model the grazing economics of settled wild game species with a known population dynamic entails improving the management of browse consumption to prevent the irreversible loss of endemic shrubs by wild game overgrazing. Finally, a critical game-rearing challenge is establishing a trade-off that integrates the interests and desires of landowners and government with respect to multifunctional forest services and products managements.

Dealing with multifunctionality in silviculture and forest management models

Multifunctionality in the silviculture and management of forest systems is widely accepted nowadays. This has been noted for some time now in literature on the subject, in which the same concept is referred to by different names. Thus Gregory (1955) used the term "multiple use", while others have employed the term "multipurpose forestry" (*e.g.*, Merlo *et al*., 1987). However, the basic idea in all these cases is the same: forest systems provide society with a wide range of market and non-market products and services of different types: provisioning (timber, forage, etc.), environmental regulating (soil erosion control, carbon uptake, etc.), and social (employment, population settlement, etc.).

Within this context, several multiple-criteria decision-making (MCDM) approaches have been used in the past decades for dealing with silviculture options in forest management problems. In fact, forestry functions, uses and purposes can be incorporated into the idea of criteria. We will now go on to summarize the main attempts in this direction.

The first MCDM approach used in forestry was goal programming (GP). This approach assigns a target to each attribute under consideration (*e.g.*, control area, closing inventory, etc.) for a harvest scheduling problem. The target represents a desirable level of achievement for the respective attribute (*i.e.*, a Simonian “satisfying” figure). The formulation of a GP model basically minimizes the function of unwanted deviations between the “satisfying” targets and the actual achievement of the different goals. There are many potential achievement functions described in literature on the topic and applied to forestry problems (Diaz-Balteiro *et al*., 2013).

Multi-objective programming tackles the simultaneous optimization of several objectives subjected to a set of constraints. Given the usual conflict that exists among forest objectives (*e.g.*, private economic profitability and carbon uptake), it seeks to determine a set of efficient solutions in a Paretian sense. Particularly useful in forestry is the bi-objective case, since it involves determining Pareto frontiers or trade-off curves, which provide basic information for dealing with silvicultural problems. Another approach used in forestry consists of determining Pareto subsets enjoying good properties. Compromise programming thus defines a subset of the Pareto set as being the set of efficient solutions nearest to an ideal point that corresponds to the optimal values of the different forestry functions being considered.

Some specific methods have been devised for discrete problems; *i.e.*, when the feasible set is formed by a finite number of forestry alternatives. This is especially relevant when we are dealing with problems related to forestry sustainability. Some of these methods are based on building a cardinal multi-attribute utility function incorporating all forest functions. However, given the difficulties associated with implementing this approach, there is a profuse appearance of surrogates based on “pairwise” comparisons among forest functions within a hierarchical structure (see Diaz-Balteiro & Romero, 2008). Other MCDM methods are employed to deal with the merging of MCDM with group decision-making methods (Diaz-Balteiro *et al*., 2009).

Finally, it should be noted that in strategic forest management a single silvicultural option is usually defined. However, in some cases, the MCDM models allow for the inclusion of other silvicultural regimes (*e.g.*, Aldea *et al*., 2012). Thus the models could be enlarged to define other silvicultural alternatives, so ensuring more sustainable management (Bravo & Diaz-Balteiro, 2004; Schwenk *et al*., 2012). Worthy of note are some illustrative examples of hybridizing different silvicultural prescriptions and MCDM methods in harvest scheduling problems (*e.g.*, Pereira *et al*., 2015, by using the knowledge of *P. pinea* silviculture in Spain shown in Montero *et al*., 2008).

Forest ecosystem extended national accounts

There is a broad consensus among national income economists and accountants that the limitations of the standard Economic Accounts for Forestry (EAF) are largely due to the narrowness of the concepts of gross value added and the standard System of National Accounts’ classification of economic activities (Stone, 1984; EC, 2000; EC-IFM-OECD-UN-WB, 2009). Another important shortcoming of the EAF is the omission of non-timber environmental income (Edens & Hein, 2013; UN-EC-FAO-OECD-WB, 2014a,b; Obst *et al*., 2016).

In this section we will look at forest income as measured by the standard EAF and by the academic extended Agroforestry Accounting System (AAS), and compare the results of the income obtained by both forest accounting methodologies. The AAS was tested in 2010 for the first time on a regional scale in Andalusian forests (Caparrós *et al*., 2016).

Standard EAF and extended AAS methodologies are derived from their respective individual product production functions and shaped by government accounting conventions and total income theory. Production factors in both methodologies are intermediate consumption (input), environmental assets, labor and fixed manufactured capital (Campos, 1999, 2000, 2015a). The differences between the two methodologies are the values omitted in the EAF of (1) intermediate products (livestock and wild game species grazing, intermediate services used for private amenity, conservation forestry services and government forestry services), (2) final product consumption of private amenity, water, carbon sequestration, public recreation, landscape conservation and threatened biodiversity preservation, (3) natural environmental growth, (4) own intermediate consumption, (5) environmental emissions of carbon dioxide, (6) used-up environmental work in progress, (7) paid self-employed labor, and (8) environmental and manufactured capital gains.

One of the key AAS extensions is the revision of the standard EAF concept of economic activity. An AAS economic activity is composed of one or more products for which it is feasible to develop full production and capital balance accounts. Going beyond the EAF, the AAS recognizes individual products as economic activities without this requiring that their production function be used up, or their being itemized as an individual cost (Campos, 2015a). Economic activities in the AAS approach are grouped into private and public, and within the same economic unit (enterprise) landowners and the government make independent management decisions. The government is represented in private activities, indirectly, by conservation forestry and, directly, by government forestry. The latter comprises firefighting and the maintenance of public livestock and walking paths. The intermediate products of both conservation and government forestry activities are used up as inputs of own intermediate consumption by the production functions of public recreation, landscape conservation and threatened biodiversity preservation activities.

The AAS system values final public product consumption of landscape conservation and threatened biodiversity above their government ordinary production cost, adding the simulated exchange values of willingness to pay declared by consumers; it also values the final product consumption of public recreation services by their simulated exchange values declared by visitors (Campos, 2015b; Caparrós *et al*., 2016 and 2017).

The standard EAF temporization failure measurement is resolved in the AAS approach by including the environmental natural growth final product. The costs omitted in EAF are avoided by incorporating own intermediate consumption, environmental emissions of carbon dioxide and used up environmental work in progress. Paid self-employed labor is estimated by the residual method as zero or positive values (Oviedo *et al.*, 2017).

The gross value added (synonymous with gross domestic product) at producer prices is the gross operating income before deducting taxes linked to production net of subsidies and depreciation (synonymous with consumption of fixed capital) and without including capital gains (net capital revaluation of adjustments). The AAS extensions described above occur in the production account and lead to the estimated net value added at producer prices as the aggregated value of labor cost and net operating margin. Labor measured by the AAS includes labor in forestry service enterprises and government employees working in forest management.

Total forest income reflects the full potential consumption of forest products during the period without reducing the real value of the forest's capital at the closing period compared with its value at the opening period. In the AAS framework, total income is estimated by adding capital gains to the net value added (Campos, 1999, 2015a). Adding environmental income and used up environmental work in progress provides forest resource income. This is considered the variable that, discounting indefinitely the values of future periodic flows, can estimate the period value of individual forest product environmental assets (UN-EC-FAO-OECD-WB, 2014b).

The main relevance of AAS measurements lies in environmental and total income. The former represents the main component of resource rent and, therefore, the individual valuation of forest ecosystem services that contribute to its total income. A comparison of the two accounting methods shows that net value added is not sufficient for estimating the real total income that forests provide to society (Caparrós *et al*., 2016; Ovando *et al*., 2016a).

We found dramatic differences between AAS and EAF income results in Andalusian forest ecosystems in 2010. The AAS measures a gross value added 11.1 times the standard EAF gross value added of 211 million euros (IECA, 2015; Caparrós *et al*., 2016).

Finally, AAS reinforces the recommendations of the European Union to extend the standard National Accounts System to obtain more reliable results for environmental and total forest income, which can then contribute to designing and implementing durable, environmentally-efficient and socially-inclusive public policies (EC, 2011).

Product self-consumption market and estimated valuations compared

Forests provide timber and many non-timber forest products (NTFP) such as firewood, hunting, cork, resin, mushrooms, wild fruits, recreational services, and endemic wild biodiversity preservation services. Some of these are present in competitive markets (*e.g.*, hunting, cork, resin) while others lie outside the market as own harvested products for self-consumption (*e.g.*, recreational services, mushroom-picking and threatened biodiversity services). Forest owners can self-consume all of these products. This self-consumption is relevant in

Mediterranean forest systems, where we can distinguish two types of product self-consumption: public (*e.g.*, free access recreation and mushroom-picking) and private (*e.g.*, hunting services and other landowner amenities). In order to obtain the self-consumption value of forest products, we need (i) silvicultural models providing the quantities available for total consumption, and (ii) a real or simulated competitive market price (Ovando *et al*., 2010). For example: Calama *et al*. (2008) have developed a silvicultural model for pine nut production; silvicultural models are also available for firewood by species (Serrada *et al*., 2008; Montero *et al*., 2015); for hunting, official statistics are available on harvesting by species and growth models. Many production models have therefore been developed for timber and NTFP (Bravo *et al*., 2011).

In an economic analysis, physical production incorporates the value of total forest products taking into account the prices of both traded and self-consumed products. These values can be implemented consistently in a standard or extended national accounting system (EC, 2000; Caparrós *et al*., 2003a). Nevertheless, the monetary valuation of self-consumption is often subject to uncertainty as well as problems stemming from asymmetric information. Standard national accounting recommends using market prices to impute self-consumption. This general rule has recently been questioned (Martínez-Jauregui *et al*., 2016b) in the event of lack of demand. In this case, the allocation of market prices does not correctly reveal the average value of self-consumed products, but rather their maximum value. Therefore both market prices (when demand is certain) and supported costs (when demand is uncertain) could be applied here. For example, the price of a substitute good in a competitive market could be used to impute the value of the self-consumed product. But if it is shown that the extracted product had no alternative demand, market prices could be replaced by operational costs (silvicultural treatment, wages, self-employment, and transportation costs), thus obtaining a lower bound of the self-consumption value.

Finally, further research on self-consumption is needed to value self-employment and prices of self-consumed products that empty the market. In regard to self-employment, the labor cost depends on a person's rationality, *i.e.*, specialized workers could play under current market labor conditions, but non-professionals could play in a comparable market with lower (or even zero) wages (Campos *et al*., 2015). Therefore, the labor cost depends on the worker's rationality criteria and current employee labor costs could constitute an upper limit for valuing self-consumption of forest products in "home-based" economies.

Private amenity self-consumption

Several studies highlight the importance that environmental amenities and lifestyle values have for private forest owners (see, among others, Campos & Mariscal, 2003; Torell *et al*., 2005; Campos *et al*., 2009; Wasson *et al*., 2013). This has been shown to be particularly relevant for the Mediterranean oak woodlands of Spain and California, where private amenities contribute significantly to the income generated by these woodlands (Campos *et al*., 2013; Oviedo *et al*., 2013, 2017).

Research over the years has shown two main implications for income accounting and management models derived from private amenity self-consumption by forest landowners. On one hand, private amenities influence land market prices, as shown by several studies using the hedonic pricing method (Pope, 1985; Torell *et al*., 2005; Wasson *et al*., 2013). This influence, however, does not translate into a directly observable market transaction of amenity services once the land is owned. In general, forest landowners decide to self-consume the amenities for which they have paid when buying the land (Campos *et al*., 2009; Huntsinger *et al*., 2010). Thus, while the woodland market price incorporates the future consumption of amenities, the value of the annual benefits associated with these amenities is not directly observable in any market, and therefore not recorded in national accounts and official statistics. On the other hand, it is expected that forest management is partly shaped according to landowner preferences for the consumption of these amenities. Therefore, silvicultural models that do not consider private amenity benefits may fall short of capturing the real behavior of landowners in the management of their stands in the long-term, and this could take the policy maker to misleading decisions if using these model results.

The estimation of the non-market output of private amenities has been done for different case studies of oak woodlands and forests in Spain, Portugal and California (Campos *et al*., 2009, 2013; Ovando *et al*., 2010; Oviedo *et al*., 2012, 2013). In all cases, this estimation was done using the contingent valuation technique. The method uses a survey to present landowners with a market simulation where they have to state the maximum annual monetary income that they are willing to pay (to give up) before selling the land and placing the money in an alternative non-agrarian investment. The main finding from these studies is that private amenities offer, on average, an additional 4% in the investment profitability for landowners. This result is particularly relevant for understanding why current landowners maintain these investments despite their low commercial profitability, and why potential buyers pay an additional premium over the market price that would be expected only if commercial production were considered when discounting benefits (the same applies to potential sellers that demand an additional premium in the selling price of their land to compensate for the loss of amenities when they sell their property).

Two main challenges remain in this research area. First, the importance of forestland amenities should be explored beyond Mediterranean-type forest ecosystems in a context without a potential change to urban land uses. Second, it is not clear how landowner consumption of amenities affects the provision of forest commodities and other public environmental services (see next section). It is expected that there will be synergies between these joint productions but so far the economic valuation of these non-market products has been done independently. Further research is needed to explore ways to meet the social commitment of providing both private and public products in forest management and how this could improve policy making for an optimal use of forest resources.

Environmental valuation of public forest products

As already discussed in previous sections, the multifunctionality of forests is now widely accepted. In addition to traditional private goods such as timber, forests are recognized for producing public products such as carbon sequestration, water services, recreation, landscape and biodiversity.

Economic valuation of these products has been an active field over the last decades, although most existing studies focus on one of these public goods. Valuation of free access recreation, landscape values and (threatened) biodiversity are typically done using non-market valuation techniques, in particular stated choice methods (Bateman *et al*., 2002, 2013). The standard procedure consists of selecting a random sample of the general population and confronting respondents with a questionnaire in which they have to state their willingness to pay to support a program that involves the provision of an environmental service. Data is then analyzed using the basic multinomial logit model and its recent developments (the mixed logit), allowing us to estimate the probability that a member of the sample (and, indirectly, the population) would be willing to pay a given amount of money. These probabilities are interpreted as a demand function that allows the estimation of different Hicksian variations (which are equivalent to consumer surplus if the income effect is small).

The results obtained are relevant for one particular public good, but it is not clear how we can integrate these with the economic values of private goods. One alternative is to use a cost-benefit analysis, in which all products are valued based on the consumer and the producer surplus (the former is what consumers are willing to pay for each unit above the price and the latter the profit obtained by the producers for that unit). Note that in order to follow this path, one needs to estimate complete demand functions for all the private goods produced.

In economic terms, a silvicultural model provides the physical units needed to fit a production function. Essentially, it tells us how much of each product can be obtained at any moment in time. Using the market values for each of the private goods produced, one obtains the production function that can be used in economic analyses. The problem is that market prices are marginal values, and simply multiplying the market price by the units produced gives an exchange value, but not the producer and consumer surplus generated. Hence, the values obtained using this procedure are not comparable with those obtained by directly using the non-market valuation techniques described above.

To overcome this difficulty, Caparrós *et al*. (2003a) proposed the simulated exchange value method. Briefly, the method consists of utilizing demand functions that are estimated using non-market valuation methods in order to simulate the entire market (demand, supply and competitive environment) and thus obtain the market value corresponding to a given ecosystem service if it were internalized. Although the method is more general and can be applied to other settings, the first paper that applied this method (Caparrós *et al*., 2003a), showed the relevance of efforts to integrate public goods and services with commercial values obtained from silvicultural models in developing this technique (the paper applies the method to recreation, among other public goods, and integrates the values obtained with commercial values for *Pinus silvestris* in the Guadarrama mountains). Subsequent studies have applied this method to different ecosystems and added other non-market public environmental services and/or private amenities (see previous section) (Campos & Caparrós, 2006; Oviedo *et al*., 2013; Caparrós *et al*., 2016, 2017; Ovando *et al*., 2016b).

Carbon sequestration and water services are other examples where silvicultural models can be effectively used to value public goods and services. Both services are typically valued using prices from other markets (emission trading markets for carbon sequestration and water prices for irrigated land) so that the discussion above on consumer surplus is not so relevant. Nevertheless, the role of silvicultural models remains paramount, as both carbon sequestration and water services valuation need detailed information on physical production of biomass, and information that can be extracted from standard silvicultural models by applying the appropriate expansion factors (Caparrós *et al*., 2003b).

Environmental asset spatial valuation of individual forests species

In recent years, there has been a noticeable effort to consider explicitly the spatial configuration of the provision of ecosystem services (ES). Likewise, there has been appreciable progress in the integration of biophysical and economic land use models to simulate the spatial and temporal patterns of production of forest ecosystem services and products at relevant spatial scales (*e.g.* Bateman *et al*., 2013; Caparrós *et al*., 2016).

A forest ecosystem is a spatially heterogeneous area in which the supply of ES is not distributed uniformly, either in space or over time. Mediterranean forest ecosystems provide a good example of this, illustrating the heterogeneity of management outcomes (both in biophysical and economic terms) under diverging ecological, climatic, geological and economic conditions. In this sense, ecologically robust forest management models (*e.g.* Serrada *et al*., 2008; Montero *et al*., 2015) are crucial for capturing spatial and temporal forest variability, given that tree growth, forest depletion and forestry management might affect the dynamics of ES supply.

A recent study by Ovando *et al*. (2017) developed an economic decision modelling framework that integrates forest growth, yield and silvicultural models along with (i) main bio-geo-physical forest attributes (*i.e.*, current species and age class distribution, tree and shrub density, slope of the land, and quality of the site for growing different forest products), (ii) forest fire and mortality rates, and (iii) detailed economic data on the costs and profits of different forestry operations. This model is used to evaluate and predict forest management decisions at the site scale, considering explicit spatial interactions among forest attributes, management models and different economic scenarios, and the effect of those decisions on the production of ES. This model has been applied in a sample of 567 silvopastoral farms distributed throughout Andalusia and the municipalities in which those farms are located.

The species included in the model are *Q. suber*, *Q. ilex*, *P. pinea*, *Pinus halepensis*, *Pinus nigra, Pinus pinaster* and *Eucalyptus* sp. The model considers 19 different forest management regimes, based on the species involved and the type of site, *e.g.*, if it is used to grow timber, cork or nuts (Diaz-Balteiro *et al*., 2015; Montero *et al*., 2015), and seven ES comprised of the provisioning of raw materials (*i.e.*, timber, cork, firewood, nuts, grazing resources and water yield) and carbon sequestration as a climate change regulating service. The forest water here refers to the fraction of superficial run-off that is captured by forest, shrublands and grassland and reaches a regulated reservoir in Andalusia. This water yield can be regulated by the water agency (collectible surplus of forest water) and allocated among final economic users. The forest water flow figures and the model used to simulate changes in water inflow due to variations in forest attributes are described in detail in Beguería *et al*. (2015).

The results of this study reveal a noticeable spatial variability in the environmental asset value associated with the provision of ES and indicate the potential trade-offs associated with silvopastoral market-based provisioning services, carbon sequestration and forest water. The results suggest an important trade-off between carbon sequestration and forest water, which is especially relevant for oak species. The latter result might have important policy implications for the design of payments for ecosystem service schemes to promote forest ecosystem conservation in Mediterranean areas. For example payments based on carbon sequestration payments might benefit areas with a higher growth potential in detriment of collective water surplus, which is a limiting factor in Mediterranean areas.

A crucial gap still needs to be closed in the integration of traditional forest ecosystem and eco-hydrology sciences within social, economic and behavioral sciences to improve decision-making (Keenan, 2015). Recent advances, such as the model developed by Ovando *et al*. (2017) based on robust forest ecology and management models and experimental data are contributing to bridging this gap. Nonetheless, more research is needed to analyze the potential fluctuations in forest growth, yields, mortality rates, forest fire patterns, forest water and adaptive forest management in response to changing climate conditions, and their impact on ES dynamics.

Optimal control silvicultural models for the management and conservation of dehesa ecosystems

Optimal control theory is a mathematical optimization method for designing control policies. The method is largely due to the works of Bellman (1957) and Pontryagin (1962). This technique is very appropriate for solving natural resource dynamic optimization problems, where it is common to seek the maximization of some measure of present discounted economic value, over some future horizon, subject to the dynamics of the harvested resource and any other relevant constraints. The solution would be a schedule or "time path" indicating the optimal amount to harvest in each period, or alternatively, a "policy" function relating yields to the stock of the resource being harvested (Conrad, 2010).

Mention must be made here of pioneering optimal control applications for agroforestry management analysis in multiple-use forests developed by Standiford & Howitt (1993). They successfully formulated an optimal control model to evaluate forest sustainability in Californian ranches, determining optimal paths for timber extractions as well as cattle herd sizes.

Mediterranean forests in Spain and California have in common climate, Spanish historical influence, ownership structure, and management. Thus, Spanish *dehesas* and Californian ranches are similar systems and present similar modelling challenges. Campos *et al*. (2007) presented and discussed two optimal control models designed to incorporate environmental and social values into the analysis of management options for Mediterranean forests. The first model reveals that including the environmental goods and amenities enjoyed by the landowner can better explain the fact that California landowners keep their oaks even if a simple financial model suggests that the optimal option is to cut them down to maximize grazing resources. The second model suggests that fast-growing alien species are the best for carbon sequestration, but the high biodiversity values of cork oak woodlands, and public preference for cork oaks over species such as Eucalyptus, increase the benefits of cork oak reforestation. This second model is developed more in depth by Caparrós *et al*. (2010).

Cerdá & Martín-Barroso (2013) present a deterministic dynamic optimization model with a finite time horizon, formulated as an optimal control problem in discrete time. Information prerequisites correspond to silvicultural cycles of artificially planted stands as well as those of natural regeneration, both under a sustainable and a non-sustainable scenario depending on the forest continuity implemented by natural regeneration practices. Required cultural interventions can then be evaluated from the economic perspective by owners and society as a whole. For a given private capital income or total social income variable, the formulated problem aims to determine optimal paths, *i.e.*, those that offer maximum present discounted value for the natural regeneration of aging stands and reforestation on bare land given a decisive time horizon. The analysis of derived solutions yields some policy-related issues worth mentioning. On the one hand, the conservation of oak *dehesa* woodlands yields the highest levels of social income. Furthermore, it is socially optimal for preservan current endowments of oak woodlands by means of natural regeneration schemes. On the other hand, private owners can only completely ensure sustainable forest management in the presence of public payment schemes justified by the provision of social benefits.

Policy and management for oak woodlands in California

In 1985 the University of California, working with the California State Board of Forestry, California Department of Forestry and Fire Protection and the California Department of Fish and Game, began a unique, multi-agency program designed to carry out research, outreach, and education in an effort to contribute to the conservation of California's Mediterranean oak woodlands (Standiford & Bartolome, 1997). The program was titled the Integrated Hardwood Range Management Program (IHRMP). California's oak woodlands are similar to the dehesa of Spain, with an understory of grasses that have in fact largely migrated from Spain and an overstory of various *Quercus* species (Allen-Diaz *et al*., 2007). Managed extensively, and mostly for firewood, game, and livestock, the post-settlement history of oak woodlands in California extends only to 1769, when the first Spanish settlers arrived, and livestock came on to the scene. For most of the history of the program, research and idea exchange between Spain and California, particularly the research groups of Montero and Campos, has played a consistent role in the development of policy and education about how oak woodlands might be conserved and managed. Perhaps most importantly, exposure to the Spanish ecosystem and the silvicultural questions that are addressed in Spain has gradually brought about the realization that the "baseline" for the contemporary conservation of California oak woodlands is no more natural than that of Europe.

Oak woodland silviculture has key differences to silviculture in conifer forests. Silviculture in the United States, started in the early 20th century, with origins from Germany and France. In the beginning it had a primary goal of assuring a secure supply of sustainably produced timber as part of supporting a modern economy. Its initial application was on forest lands managed by the federal government. In recent years, it has broadened to include private timberlands. The IHRMP was one of the first times that silvicultural systems were utilized in California to accomplish grazing, hunting and production of ecosystems services. California has some of the strictest forest practice regulations and laws in the United States, regulating timber harvest and restocking on private lands. While the field of course expanded and became more inclusive through the 20th century, the Integrated Hardwood Range Management Program raised the need for significant divergence from traditional silvicultural and forest management models: California's oak woodlands are mostly privately owned, and do not fall under the laws that regulate forest harvest; landowner goals are diverse and rarely include timber in the conventional sense; unlike in many forests, income from timber or firewood is not necessarily greater than that from grazing, game, or other products; and regeneration of oak trees is slow, sporadic, and somewhat unpredictable in the field. In recent years, the need to recognize oak restoration as a silvicultural goal in oak stands being invaded by Douglas-fir as a result of fire suppression, has also forced a change in the traditional forest practice regulations in the state (Valachovic *et al*., 2015).

The collaborative research and exchange with Spain contributed ideas in each of these areas. Because landowner goals are diverse, it became important to develop management models that include diverse goals for woodlands. The *Guidelines for Managing California's Hardwood Rangelands* (Standiford, 1996) developed as a result of the program, included silvicultural models for oak growth, as well as models for livestock and game production. *A Planner's Guide to Oak Woodlands, 2nd Edition* arose out of the need to improve land use planning for oak conservation, and emphasizes the many ecosystem services from oak woodlands (Giuisti *et al*., 1992). Economic studies supported by the program revealed the value of oak woodlands to surrounding properties using Hedonic pricing (Standiford & Howitt, 1993; Standiford & Scott, 2001). A significant issue in Spain and California alike is sustaining production while making certain there is natural regeneration and recruitment of the oaks.

Spanish and Californian oak woodlands provide a diverse array of woodland-produced commodities, including forage, firewood, acorns, habitat, game, and amenities. Several silvopastoral models exist for analyzing such production. The silvopastoral modeling efforts in the Spanish dehesa and in California oak woodlands revealed the important linkage of multiple outputs with realistic cost and return data (Standiford *et al*., 2013). For the Spanish dehesa, silvopastoral modeling indicated that even if not as profitable as grazing alone, given current social preferences and the shortcomings of the government's land use policy, investment in tree regeneration and development is needed in order to protect options for providing commodities and amenities for future generations (Montero *et al*., 2000). Implementing accurate compensation schemes may be the key to long-term holm oak dehesa conservation, the short-term cash losses required to invest in dehesa regeneration may not be feasible for landowners. Modeling provides insights into the income losses that private owners may incur from grazing restrictions and natural oak regeneration treatments. Future research is needed to improve scientific and policy knowledge regarding the minimum payments and the appropriate compensation schemes needed to induce dehesa owners to invest in the regeneration of aging oak woodlands (Ramírez & Díaz, 2008). This would help mitigate long-term biodiversity loss and at the same time potentially boost landowner amenity and financial benefits from dehesa improvement and afforestation.

For California oak woodlands, modeling efforts revealed the importance of incorporating actual landowner behavior into findings derived from current cost and return data. Policy analysis needs to carefully take into account that landowners receive value from maintaining certain levels of oak stands (Standiford & Howitt, 1990). As the interrelationships between the various products from silvopastoral systems become better understood, enhanced modeling efforts are possible. In addition, new markets, especially for ecosystem services and carbon sequestration, are expected to create new opportunities for sustainable silvopastoral management outcomes.

Survey research of California landowners starting at the outset of the IHRMP showed that landowners were motivated by the benefits of living and working in the oak woodlands more than by maximizing monetary profit (Huntsinger *et al*., 2010). This early work has been further developed by consideration of the Spanish experience and in research collaboration. Comparative research has refined the many privately consumed ecosystem services that motivate landowners and land use, and illustrated how to place monetary value on these non-market services (Oviedo *et al*., 2012, 2013; Campos *et al*., 2013; Caparros *et al*., 2013).

Gregorio Montero, one of the Spanish scientists that visited California as part of our research exchange, in particular assured us from the outset that our oak woodlands and savanna had been influenced by human action. We, in turn, assured him that our woodlands are "natural," and that their open character was a function of soils and climate, unlike the heavily managed woodlands of Spain. However, as time has passed and we have more and more opportunities to observe the impacts of grazing restriction and fire exclusion, we see brush encroachment − though relatively slow encroachment in Spanish terms − in many areas. For more than a few of us, it has become clear that the activities of Native Americans, most particularly the burning carried out by Native Californians, shaped our own oak woodlands. With that element lost, we are, in fact, operating in a "novel ecosystem," where previous anthropogenic ecosystem drivers are no longer operate in most of the woodlands, new species have supplanted the understory, and livestock grazing affects most of the area. This knowledge will allow us to better contextualize the developing body of research on oak woodlands, and understand the impacts of management practices such as exclusion of fire and grazing.

Challenges of integrating different forest management types into ecosystem accounting

The main challenge of biophysical modeling of forest ecosystems silvicultures entails improving our scientific knowledge of both the expected individual ecosystem services and full product outcomes deriving from landowner and government managements (Montero *et al*., 2015).

On the demand side, estimating prices and quantities of non-market product consumption undoubtedly constitutes the biggest challenge in the ongoing revision of national forest accounts. An additional challenge from the perspective of non-market valuation is modelling the evolution of some public and private environmental services using available scientific knowledge to construct prospective scenarios for forest ecosystems. Current applications do this for carbon sequestration and water but not for other environmental services such as public recreation or biodiversity preservation. This information would allow us to design market simulations that estimate different demand functions for different periods over the entire cycle of the forest stand rather than assuming a constant flow of environmental services. Natural growth and environmental net asset revaluations of destruction estimates are key challenges from the supply side in order to achieve real measurements of environmental income, resource rent and total income from forests.

Consistently integrating the values of products with and without formal market pricing by using the simulated exchange value method presents a breakthrough that enables governments to adopt a revision of national accounts. This reduces the current gap between standard and extended gross domestic product measurements.

Economic science offers no consistent response to channeling the total income obtained to prevent the loss of genetic diversity in the long term. The extended accounting of forest ecosystems offers sustainable income that derives from the willingness to pay of current generations, but as this may not take into account wise prices for valuing endangered biodiversity and protecting it from permanent destruction, these values have to be interpreted carefully. Although this is a debatable issue, the government may have a role to play on behalf of future generations by imposing a tolerable total loss of income on current generations to guarantee the preservation of threatened biodiversity.

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