Chapter 9
Models of Oak Woodland Silvopastoral Management

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Frontispiece Chapter 9. A thinned blue oak stand in the Northern Sacramento Valley of California, shows coppice regeneration and forage growth. (Photograph by R. Standiford)

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Abstract Spanish dehesas and California ranchlands provide a diverse array of woodland-produced commodities, including forage, wood, acorns, habitat, game, and amenities. Several silvopastoral models exist for analyzing such production. An examination of management scenarios that include encouraging natural regeneration in dehesa is offered, and then compared with management where no extra inputs are provided and the tree overstory is gradually lost over time. A significant issue in Spain and California alike is sustaining production while making certain there is natural regeneration and recruitment of the oaks. A sensitivity analysis of public inputs, product prices, and discount factors is provided. Silvopastoral models for California woodlands illustrate the importance of incorporating actual landowner behavior in policy analysis to accurately represent the future trajectory of oak woodlands.

Keywords Silvopastoral systems • Multi-functionality • Oak natural regeneration • Market and non-market incomes • Positive mathematical programming • Bioeconomic models • Optimal control

9.1 Introduction

Silvopastoral management of oak woodlands in California and Spain commonly provides fuelwood from oak and shrub clearing or tree pruning (Fig. 9.1), fodder (acorns, grass and browses), cereal fodder in long rotations, wild game, honey, and other diverse private goods and services (Moreno et al. 2007). In addition to these traditional uses, California oak woodlands and the Spanish dehesa provide ecosystem services of growing interest to the public and policymakers, including recreational opportunities, carbon storage, and wildlife habitat (Chaps. 8, 11, 12). A continued supply of such goods from private oak woodlands in California and Spain depends on owners receiving monetary and non-monetary benefits greater than the opportunity costs of forgoing competing land uses.

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Fig. 9.1 Firewood, even in fairly recent history (1960s), was a staple fuel in Spain, especially when converted to charcoal, and wood pruned from holm and cork oaks provided a ready source of fuel for energy. While that market decreased in the 1960s with propane and oil-based heating, thanks to a rising Spanish interest in barbecuing and wood-based cooking, firewood retains some value (Elena-Roselló et al. 1987) (Photograph by P. F. Starrs)

In this chapter two general approaches are described for assessing silvopastoral management systems. A silvopastoral model for western Spanish holm oak (*Quercus ilex* L.) dehesa allows evaluation—using an extended cost-benefit approach—of a managed, or facilitated, natural regeneration project over the entire productive cycle (rotation) of woodland in Monfragüe shire in Extremadura. This woodland is part of the buffer zone that surrounds Monfragüe National Park. For California oak woodlands, an optimal control multi-objective silvopastoral model is presented, showing the influence of the interrelationships of grazing, firewood harvest, and hunting on optimal economic outputs.

9.2 A Spanish Dehesa Silvopastoral Model

There are two important trends in the dehesa of southwestern Spain that are important to dehesa conservation. First is a marked recent decline in dehesa productivity and profitability due to poor oak regeneration, which is most commonly attributed to unrestricted grazing (Díaz et al. 1997; Pulido et al. 2001; Pulido and Zapata 2006; Plieninger 2006, 2007). Estimates based on the Spanish National Forest Inventory show that in dehesa areas of Andalucía, Extremadura, and Castilla-La Mancha, natural regeneration is insufficient or nonexistent in more than 60 % of holm oak and in 95 % of cork oak woodlands (MARM 2008, 2011). The second trend is a moderate long-term appreciation in real land price. From 1994 to 2010 the nominal and real average cumulative rate of Spanish dry natural grassland price change was 5.68 and 2.65 %, respectively (MARM 2011). With low commercial profitability from traditional silvopastoral management, land price appreciation is tied to increases in the amenities enjoyed by private owners (Campos and Riera 1996; Campos 1997; Campos et al. 2009; Chap. 13).

The lack of natural oak regeneration in the dehesa is unsustainable from the perspective of tree-related yield of goods and services such as acorns, firewood, browse and wildlife. While the current management regime with poor oak regeneration appears to generate competitive private profitability rates, especially when considering increasing prices for dehesa properties, private amenity values, rental fees for hunting of wild game, livestock grazing, and various government subsidies, there are long periods of negative cash flow that accompany afforestation efforts or facilitated natural regeneration of oaks (Campos et al. 2008a, b). This makes regeneration of the dehesa commercially unattractive to many private landowners, who base their decisions on past—and even historical—trends. That may be short-sighted with respect to opportunities for the production of future goods and services (Martín et al. 2001; Campos et al. 2008a).

Economic analysis of facilitated natural regeneration for holm oak woodlands requires development of a management model, incorporating growth and yield functions from the beginning of the regeneration treatments to the end of holm oak production cycle. For this purpose, we use the set of forestry operations described in a model developed by Montero et al. (2000). This offers information on diameter growth, acorn and firewood yields, implemented in a management scheme that is tracked through an entire rotation cycle (Fig. 9.2).

The holm oak production cycle is modeled here over a 250–year rotation for the Monfragüe holm oak dehesas. This shire has a surface area of 133,282 ha, covering the territories of seven municipalities. The useful agricultural land (UAL) is mainly dehesa (43 % of UAL), and dryland pasture and temporary grain fields (19 % of UAL), as tabulated by Campos et al. (2008a). Extensive livestock production is important in the Monfragüe shire, although increasing livestock grazing pressure hinders natural regeneration (Chap. 5; Campos et al. 2001; Pulido et al. 2001; Rodríguez et al. 2004; Pulido and Zapata 2006; Plieninger 2006, 2007).

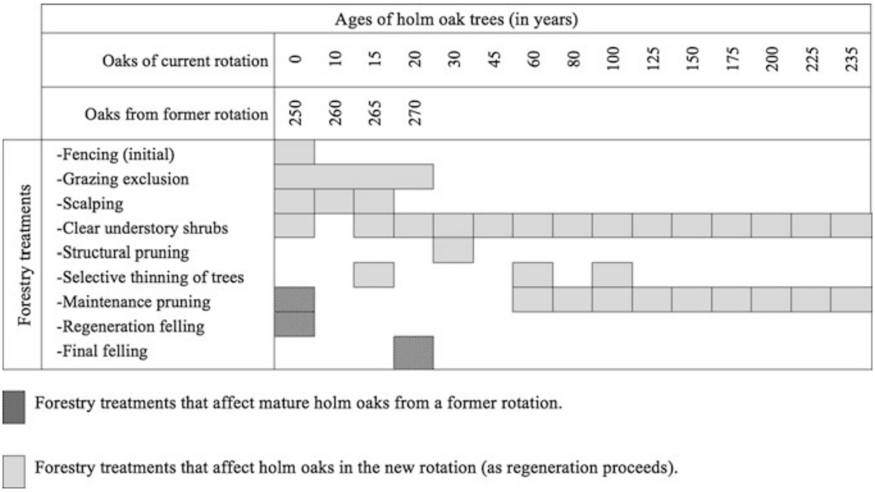

Fig. 9.2 A forestry operations schedule for the dehesa holm oak management model of facilitated natural regeneration

9.2.1 Dehesa Holm Oak Growth Functions

Diameter growth throughout the life cycle of an oak tree is a good indicator of stand development, and of its capacity to produce timber and firewood. Normal diameter growth determines the basal area growth in even-aged holm oak stands.

Holm oak diameter growth is estimated from annual growth data from 34 holm oak trees collected from oak rounds measured at breast height (dbh = 1.30 m). This data was used to fit a Richards-Chapman function, with a mean error of 4.0 cm and adjustment coefficient (R^2) of 0.86:

$$d_{sc}(cm) = 115.528 \cdot \left(1 - e^{-0.00644568 \cdot t}\right)^{\left(\frac{1}{0.987524}\right)} \tag{9.1}$$

where d_{sc} is the diameter (in cm) without bark at breast height (1.3 m), and t is the estimated oak age (normal age). It is assumed that the real oak age equals to t + 10, assuming that holm oaks take 10 years to reach 1.3 m in height, after being planted or recruited.

9.2.2 Holm Oak Silvopastoral Management Model

The prescribed treatments for facilitating natural regeneration include 20-years of grazing exclusion (using fences of a height sufficient to exclude deer), structural tree pruning, selective tree thinning, shrub clearing, and regeneration felling (Fig. 9.2). During the 20-year grazing exclusion period, both the quantity of forage

Table 9.1 Key yield and input indicators of facilitated natural regeneration investment and non investment scenarios for the entire cycle of holm oak

Class	Unit	Quantity (units hectare^{-1})	
		Total cycle	Annual
Investment scenario (250-year)			
Firewood	kg	428,453	1,714
Maintenance pruning	kg	16,206	65
Oak trees felling	kg	412,247	1,649
Forage estimated consumption	FU[a]	41,952	168
Acorns (total biological yield)	kg	140,110	560
Acorns (montanera)	kg	67,253	269
Acorns (big game)	kg	33,561	134
Working hours	hour	2,437	9.7
Machinery and equipment	hour	816	3.3
Non-investment scenario (70-year)			
Firewood	kg	80,267	1,147
Maintenance pruning	kg	1,427	149
Oak trees felling	kg	6,840	998
Forage estimated consumption	FU[a]	12,768	182
Acorns (total biological yield)	kg	10,454	149
Acorns (montanera)	kg	5,018	72
Acorns (big game)	kg	2,509	36
Working hours	hour	441	6.3
Machinery and equipment	hour	162	2.3

[a] *FU* forage unit

units (FU)[1] consumed by livestock in oak woodlands and acorn consumption in the *montanera* period (Chap. 10) must be reduced under the natural regeneration scenario (Table 9.1). This exclusion period is needed, and required under government subsidy policy, to reduce browsing damage to regenerating oaks.

Regeneration felling is the initial treatment to facilitate natural regeneration. This involves cutting a large percentage of aging holm oak trees to enhance on-site seeding under the tree canopy, without completely forgoing ongoing firewood yields from the remaining trees through the regeneration and recruitment period. The most productive trees are left standing until the final clear-cut of remaining mature trees takes place. The model posits three consecutive felling operations to assist regeneration. At first felling, left in place are 20 or more well-distributed high acorn yielding trees per ha. After a decade, a second regeneration felling is scheduled, leaving at least 15 older trees/ha. A third felling is scheduled twenty years after the first felling, and removes the remaining mature holm oaks. This is timed to match an end to the grazing exclusion period (Figs. 9.2). By then, the number of oaks per ha is considerable lower and more typical of dehesa (Figs. 9.3).

[1] A forage unit (FU) represents the energy contained in a kilogram of barley at 14.1 % humidity, or 2,723 kilocalories of metabolic energy (INRA 1978).

Fig. 9.3 Young holm oak trees from natural regeneration with recent structural pruning to transform them from shrubs to a tree-like form (Badajoz, Spain) (Photograph by A. Adamez)

This prescription results in a seedling density of some 3,000 stems per hectare, which will decrease to 2,000 oaks per hectare after 16 years following the first thinning and a shrub clearing. Thinning treatments reduce competition from weak trees, favoring the growth of the residual trees. It is assumed that diseased trees are removed simultaneously with periodic shrub clearing every 25 years to favor oak tree growth by reducing competing vegetation and disease spread.

Finally, the model has one formation pruning of the regenerating oaks when they reach the age of 31 years (real age), coinciding with the second thinning and a periodic clearing of understory shrubs (Fig. 9.4). In addition, the model includes cyclical maintenance pruning to encourage acorn yield (although efficacy of such treatments are now questioned, Chaps. 5, 7), to balance the coppice form (as semi-round), to obtain firewood, and to provide livestock browse. Pruning operations should not affect more than one-third of the coppice biomass.

9.2.3 Firewood and Acorn Yields

Firewood is a byproduct of forest management operations that comes from maintenance pruning, sanitary felling, and thinning (Figs. 9.4, 9.5, 9.6). The linear function estimates published by Montero et al. (2000) relate firewood yield to oak tree diameter, both for firewood resulting from pruning and from tree felling treatments. Thinned trees are assumed to have a diameter 35–40 % lower than the average diameter of the holm oak stand, with a 75 % firewood yield, based on lower intensity management than the empirical data used by Montero et al. (2000).

Fig. 9.4 Recently pruned holm oak dehesa (Salamanca province, Spain). The wood obtained as byproduct of maintenance pruning can be used for posts, firewood, or in charcoal preparation (Photograph by P.F. Starrs)

Fig. 9.5 Wood posts gleaned from the thinning of wild olive trees in the dehesa Montes de Propios of the Jerez de la Frontera Municipality. After curing, these are used for fencing (Photograph by P. Campos)

For felling of diseased trees (sanitary felling) it is further assumed that only 50 % of the resulting firewood will be commercialized. Firewood yield estimates for the entire holm oak natural regeneration scenario and its alternative non-regeneration scenario are displayed in Table 9.1.

Fig. 9.6 **a**, **b** The traditional method of charcoal preparation consists of covering a woodpile with soil and straw, allowing only a small amount of air to enter. The wood sticks burn very slowly in a "cold fire" and become charcoal. **c**, **d** Charcoal loaded in bags for transport and sale (Photographs by P. Ovando)

Acorn yield in Mediterranean areas is characterized by considerable annual variation (Chap. 8). There are periods with high acorn production, followed by a varying number of years with low to moderate yields (Chap. 7; Pulido and Díaz 2003). Montero et al. (2000), in an article based on existing literature and experimental data, provide a set of hypotheses for estimating acorn yield along the entire productive cycle of a holm oak. It is assumed that holm oak acorn yield starts having commercial value when oak trees are 21 years old at about the time the grazing exclusion period comes to an end. During the early stages of oak growth, from years 21–49, data used are from Rupérez (1957). From year 50 to 99, acorn yield based on the estimates provided by González and Allue (1982). From year 100 to the end of tree's productive cycle data is from Vázquez et al. (1999). Furthermore, 20 % of acorn biological yield is assumed not to be available for livestock and game animals due to insect and rodent depredation and other environmental effects (Díaz et al. 2011; Chap. 8). Figure 9.7 provides information on average acorn yield per oak tree and the number of productive oak trees per hectare throughout the holm oak rotation.

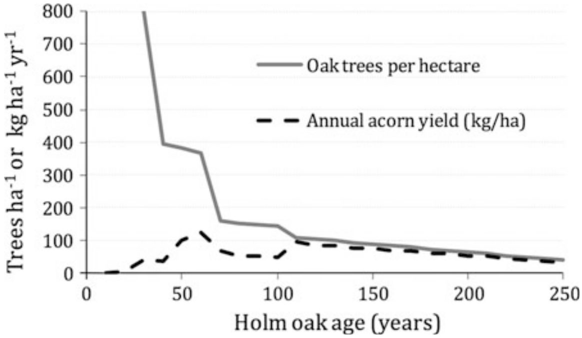

Fig. 9.7 Average oak tree density and acorn yield per hectare and year through the entire holm oak productive cycle

9.2.4 Cost-Benefit Analysis: Alternative Holm Oak Dehesa Management Scenarios

The facilitated natural regeneration economic cycle lasts 250 years, the time between two regeneration fellings. If no supplemental regeneration treatments are applied at the time of the regeneration felling, holm oak will gradually disappear. If no grazing exclusion is implemented, the recruitment is unsuccessful and oaks will slowly decline and the dehesa will be converted into a treeless pastureland (Fig. 9.8).

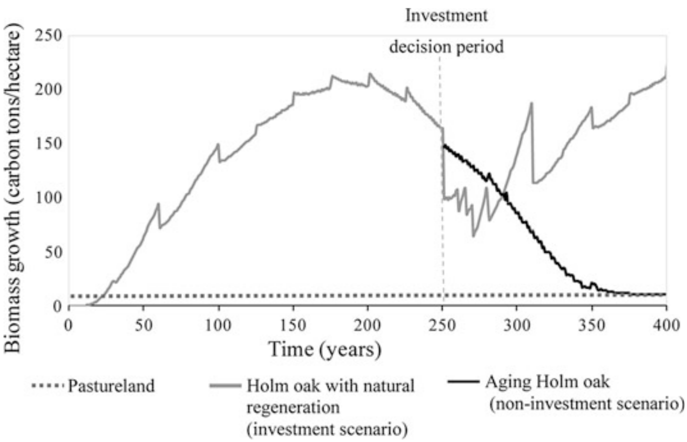

Fig. 9.8 Facilitated holm oak natural regeneration investment and non-investment scenarios

9.2.5 Private Market and Non-market Outputs from Alternative Management Scenarios

Our scenario is for a nonindustrial holm oak woodland private owner with mixed low-risk investor-consumer rationality. The private landowner is assumed to require commercial returns, while also deriving private amenities from the woodland environmental services (Ovando et al. 2010). In our models, the landowner is assumed to obtain private capital income from sales of firewood (F), acorns (A), rent from grazing resources other than acorns (GR) and hunting (HR), supplemented by government net subsidies for forest management, and the enjoyment of private amenities (PA) (non-market private consumption of environmental services internalized in woodland market prices). Constant prices are assumed to correspond with actual prices (sales, net subsidies, and costs) or with estimated prices for private amenities in 2002. We present a sensitivity analysis of the effect of discount rates, market prices for acorns, grazing resources, and government subsidies. To aggregate commercial and environmental benefits in a consistent manner, we use simulated exchange prices for private amenity values (Campos et al. 2009).

Except for private amenity value, woodland private benefits is based on direct market prices. Big game hunting income is determined by what landowners would be paid for leasing their land for hunting, net of costs and taxes. Grazing income (only for forage) reflects the market prices for leasing one hectare of holm oak woodland, or leasing open pastureland for livestock forage (Campos et al. 2001; Rodríguez et al. 2004). Acorns are valued based on the price a dehesa owner gets for each kilogram of Iberian pig weight gain during the *montanera* period and the acorn consumption needed to yield that gain (Table 9.2). Of the acorn yield, 32 % is assumed to be consumed by wildlife (especially red deer and wild boar), and 48 % feeds Iberian pigs. Acorn consumption by big game is valued at 60 % of the price of acorns in the montanera period (Chap. 10).

Private amenity value is a non-market ecosystem service that the dehesa landowner might consume, having the right to exclude other potential users or consumers. These environmental uses include private recreational services, the ability to house and entertain friends, enjoyment of a countryside quality of life, and a number of passive uses (legacy, option, and existence values). Future income streams from private amenities are capitalized into land market prices since owners and buyers have that in mind when they consider owning and maintaining a dehesa, and they are willing to pay for these private uses when they decide to maintain a property or to buy a piece of land. Indeed, private amenities have been recognized by the scientific literature as a factor in land prices (Campos and Riera 1996; Campos 1997; Torell et al. 2001; Lange 2004; Campos et al. 2009).

In this study, the private amenity value comes from a contingent valuation survey applied to a sample of 19 dehesa owners in the Monfragüe area (Campos and Mariscal 2003), updated to 2002 prices.[2] Private amenities reflect the maximum cash losses that Monfragüe owners would be willing to accept (WTA) compared with the private environmental uses provided by owning a dehesa. It is assumed that the private amenity value aggregates all dehesa owner environmental unpriced uses without differentiating any single use (Table 9.2).

9.2.6 Holm Oak Management Costs and Government Grants

Facilitated natural regeneration[3] and alternative non-investment scenarios consider only forest management costs (Table 9.2). The economic information used to estimate the work units (labor and machinery) and costs related to diverse forestry operations have been collected in the Monfragüe shire (Rodríguez et al. 2004). This study also considers government grants for forestry treatments in the Extremadura region (Table 9.2) net of taxes on production (DOE 2002).

Cost items that are taken into account are the same as those the conventional System of National Accounts (SNA) considers to estimate forest total and capital incomes (Eurostat 2000). Total cost is estimated as the aggregation of labor cost (LC) and the intermediate consumption of raw materials (RM) and services (SS). Consumption of fixed capital (CFC) is not accounted for since annual investment in fixed capital goods (only fences, in this case) match consumption.

9.2.7 Capital and Total Income Net Present Value, and Holm Oak Investment Versus Non-investment Scenarios

We apply cost-benefit analysis tools to estimate the net present values (NPV) of all future streams of private capital income resulting from the silvopastoral management scenarios analyzed. The streams of private benefits and costs are discounted using the estimated real profitability rates that landowners get from land uses prior to afforestation (Ovando et al. 2010). This represents the private opportunity cost of capital for land investment at the study sites. The estimated annual private profitability rate is 5.5 % in the Monfragüe shire, although a sensitivity analysis is provided showing discount rates ranging from 1 to 8 %.

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[2] The contingent valuation survey was conducted in 2000 with results subsequently updated to 2002 prices. We assume that private amenity value has the same temporary variation as the market price of non-irrigated pastureland in the Extremadura region (MAPA 2003).

[3] Facilitated natural regeneration for oak trees is required in dehesa to build a tree layer. Regeneration of oaks based only on natural processes does not occur in open spaces. The dehesa is a fragile working landscape maintained by livestock, avoiding overcutting of biomass to meet human demand.

Table 9.2 Market and environmental benefits prices, government grants and forestry management costs in Monfragüe

Class	Unit	Price (2002 \$ unit^{-1})
Market benefits		
Firewood	kg	0.06
Grazing rent (additional to montanera)	ha	53.30
Acorn[a] (1.71 \$ kg hwg^{-1}/9 kg acorn kg hwg^{-1})	kg	0.19
Hunting rent	ha	6.46
Environmental benefits		
Private amenity	ha	95.19
Government grants[b]		0.00
Oaks structural pruning	tree	0.71
Oaks maintenance pruning	tree	2.57
Selective thinning (trees with a diameter < 18 cm)	tree	0.21
Shrub clearing	ha	114.00
Forestry management cost		
Fencing	ha	714.59
Shrubs clearing	ha	116.95
Structural pruning	tree	2.37
Selective thinning (trees with a diameter < 18 cm)	tree	0.27
Selective thinning (trees with a diameter > 18 cm) [c]	tree	15.68
Maintenance pruning[b]	tree	12.26
Regeneration felling	ha	3,035.92
Final felling	ha	1,281.74

[a] hwg: pig weight gain in montanera period
[b] DOE (2002)
[c] Average value

9.2.8 Capital and Total Annual Incomes

We estimate the present values of capital income gains or losses as the difference between discounted capital incomes obtained from the facilitated holm oak dehesa natural regeneration investment scenarios and the discounted capital incomes generated by an aged holm oak non-investment scenario (defined earlier).

Capital income (CI_{pp}) at producer prices is an annual income indicator that reflects the difference between total benefits (TO), derived from market output sales, and private amenity consumption and total cost (TC) associated with holm oak dehesa management. The dehesa landowner business objective is the capital income at basic prices (CI_{bp}). The difference between producer price[4] and basic price indicators is that the latter includes subsidies (S) net of taxes (T) on production:

[4] Prices before government intervention via subsidies and taxes on products.

$$\mathrm{CI_{pp}} = \mathrm{TO} - \mathrm{TC} = \mathrm{F} + \mathrm{A} + \mathrm{GR} + \mathrm{HR} + \mathrm{PA} - \mathrm{LC} - \mathrm{RM} - \mathrm{SS} \quad (9.2)$$

$$\mathrm{CI_{bp}} = \mathrm{CI_{pp}} + \mathrm{S} - \mathrm{T}. \quad (9.3)$$

Total annual income at producer prices ($\mathrm{TI_{pp}}$) and at basic prices ($\mathrm{TI_{bp}}$), are estimated by adding labor cost to $\mathrm{CI_{pp}}$ and $\mathrm{CI_{bp}}$, respectively:

$$\mathrm{TI_{pp}} = \mathrm{CI_{pp}} + \mathrm{LC}. \quad (9.4)$$

$$\mathrm{TI_{bp}} = \mathrm{CI_{pp}} + \mathrm{LC} \quad (9.5)$$

9.2.9 Net Present Value Indicators

Net present value (NPV) of the expected stream of private capital incomes considers an infinite sequence of holm oak facilitated natural regeneration cycles. For non-investment scenarios, once oak trees disappear due to mortality and lack of regeneration, treeless pastureland is assumed to be the permanent land use. The capital value of a hectare of holm oak dehesa that is managed as scheduled by the facilitated natural regeneration model ($V_{n,\infty}$) is estimated considering the following equations:

$$V_n = \sum_{j=t}^{T_n} \delta^{t-1} y_n(t), \quad (9.6)$$

$$V_{n,\infty} = \left[\left(1 + \delta^{T_n} + \delta^{T_n \cdot 2} + \delta^{T_n \cdot 3} \cdots\right) V_n\right], \quad (9.7)$$

$$V_{n,\infty} = \left(\frac{1}{1 - \delta^{T_n}}\right) V_n \quad (9.8)$$

where y_n represents the value of any income variable (in one hectare) in any year of the economic cycle of facilitated natural regeneration where rotation length is defined by T_n ($\mathrm{T_n} = 250$ years); and δ represents the intertemporal discounting function: $\delta = 1/(1 + \mathrm{r})$, being r the annual discount rate.

For a non-investment scenario with no regeneration treatment, after 70 years, holm oaks are assumed to disappear. The net present value of a 250 year old holm oak stand with no regeneration treatment is estimated according the following equation:

$$V_{wr} = \sum_{j=t}^{T_n+70} \delta^{j-t} y_{wr}(t), \quad (9.9)$$

Without regeneration, an aging holm oak stand will be replaced by treeless pastureland used for livestock rearing with no grazing exclusion periods, which have annual incomes defined by y_j. Thus, the net present value of an aging holm oak result with no regeneration, converting to pastureland ($V_{n \to j,\infty}$), is estimated according to:

$$V_{wr \to j,\infty} = V_{wr} + \delta^{T_n+1}(1 + \delta^1 + \delta^2 + \ldots)y_j(t), \tag{9.10}$$

$$V_{wr \to j,\infty} = V_{wr} + \delta^{T_n+1}\left(\frac{1}{1-\delta^{T_n}}\right)y_j(t). \tag{9.11}$$

9.2.10 Results of the Dehesa Silvopastoral Scenarios

The present values of the expected stream of capital and total private incomes from the facilitated holm oak natural regeneration scenario, and the alternative non-investment scenario of gradual depletion of holm oak woodland, shows the present value of an infinite series of facilitated natural regeneration cycles compared to the present value of aging holm oak woodland that is permanently replaced by bare pastureland once oak trees disappear due to mortality and lack of natural regeneration (Table 9.3).

Two NPV indicators are considered: (1) the net present value of the stream of expected market and non-market outputs minus the expected costs from the facilitated natural regeneration scenario; and (2) the net benefits that show the difference between the NPV of the investment scenario of facilitated natural regeneration and non-investment scenario. These indicators are useful in the analysis—given current market benefits and governmental grants to holm oak management—to determine if renewing an old holm oak stand with treatments to encourage natural regeneration is an attractive investment for dehesa landowners.

Table 9.3 Net present value (NPV) of capital and total private incomes for investment and non-investment scenarios for facilitated holm oak natural regeneration ($ per hectare, year 2002)[a]

Class	Investment scenario: Facilitated holm oak natural regeneration A	Non-investment scenario: Aging holm oak B	Net benefits NPV C = A − B
Net present values	$V_{n,\infty}$	$V_{wr \to j,\infty}$	
Capital income at producer's prices (CI_{pp})	920.17	2,401.13	−1,480.96
Capital income at basic prices (CI_{bp})	1,326.30	2,547.81	−1,221.51
Total income at producer's prices (TI_{pp})	5,011.06	3,732.36	1,278.70
Total income at basic prices (TI_{bp})	5,417.28	3,879.04	1,538.24

[a] Present discounted values for an infinite time horizon frame. Discount rate: 5.5 %

The present value of the expected stream of outputs from the scenario for facilitating holm oak natural regeneration exceeds the value of the expected costs of those treatments (Table 9.3). The value of $V_{n,\infty}$ is positive, even if a dehesa owner receives no governmental grants for holm oak management (CI_{pp}). Nonetheless, letting a holm oak stand gradually decline is more profitable to the dehesa owner ($V_{wr\rightarrow j,\infty}$), and requires no initial investments for grazing exclusion fences and regeneration felling treatments (Table 9.2). In the non-investment scenario, landowners do not have a 20-year grazing exclusion period, and benefit from the revenues of leasing the land for hunting or using the land for livestock production.

These results suggest that facilitating holm oak natural regeneration offers a positive present value, even in a situation without governmental support for forest management operations. Nevertheless, under current market prices and governmental support conditions, facilitated holm oak natural regeneration cannot compete with a scenario of gradual forest decline due to aging and no recruitment.

Since private amenities are assumed to have the same value for all the land uses, it follows that the benefit from investment projects are entirely due to the discounted value of private commercial capital incomes. The effect of gradual depletion of holm oak on private amenity values is unstudied for the Monfragüe region. Nonetheless, recent research suggests that private amenity value is positively related to the proportion of forest area in southwestern Spanish cork oak woodlands (Ovando et al. 2010). A decrease in the holm oak tree population in dehesa as result of insufficient investment in holm oak renewal is likely to affect private amenity consumption.

Over the last fifteen years, the European Union and the Spanish government have strongly encouraged holm oak afforestation in pastureland, shrubland, and cropland, under the European Regulations 2080/92 and 1257/99 (Ovando et al. 2007). Those government aids promulgated in 2002 cover plantation costs, including fencing, 5 years of plant maintenance payment, and 20 years of financial compensation for grazing exclusion from the regenerating area. The European Union's (EU) ongoing policy reform in rural development focuses on multifunctional agriculture in compliance with the EU's environmental goals, which include mitigating biodiversity losses and climate change. This new rural development scheme may add government support to natural woodland regeneration practices in European agroforestry systems. Facilitated natural regeneration in the dehesa could be an efficient option for maintaining and even increasing the dehesa's current carbon stock and biodiversity (Díaz et al. 1997; Campos et al. 2008a).

Our results indicate that the 20-year compensation for grazing exclusion, which in 2002 rose to \$165 ha^{-1} year^{-1} for dehesa and treeless pastureland, would generate enough incentives to pursue a facilitated natural regeneration project for holm oak (BOE 2001). Natural regeneration investment would still be competitive when compared to the non-investment scenario, even considering 20 years of compensation for grazing exclusion that is 25 % lower than that for afforestation projects in pastureland and dehesa under EU Regulation 1257/99 in Spain (Fig. 9.9).

Livestock and wildlife grazing pressure can seriously hinder holm oak regeneration capacity (Díaz et al. 1997; Pulido et al. 2001; Pulido and Zapata 2006;

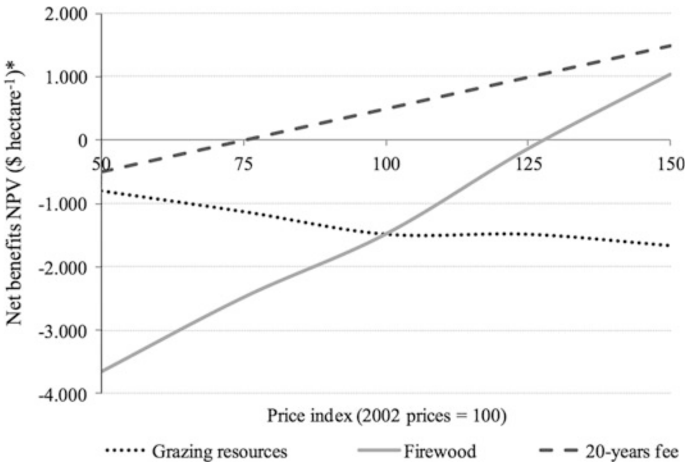

Fig. 9.9 Sensitivity of net benefits at basic prices, which includes subsidies net of taxes on products, of facilitated natural regeneration investment in holm oak to variation in prices of grazing resources, firewood and 20-year payments. *Note* *Average euro/dollar exchange ratio in 2002: 1 euro (€) = 0.95 US dollar ($) (BDE 2012)

Pulido and Díaz 2003; Plieninger 2006, 2007). Since the regeneration investment scenario implies 20 years of grazing exclusion, simulation of the effect of changes in the price for grazing resources (forage and acorns) on dehesa owner NPV capital incomes (CI_{bp}) may be crucial in driving this investment decision. Indeed, a decrease of 50 % in montanera (acorn) and grazing rent prices is not even enough to make facilitated natural regeneration scenario more competitive than letting the holm oak woodlands move instead toward open pasture land (Fig. 9.9).

However, the net benefits of the holm oak facilitated natural regeneration scenario are quite sensitive to firewood price variability. An increase of 27 % over current firewood prices would make the investment scenario a more attractive alternative than the non-investment one, since firewood is a byproduct of regeneration felling (Fig. 9.9). It is worth mentioning that under current dehesa rules, an increase in firewood prices may not be an incentive for harvesting dehesa oaks since those trees are highly protected and the dehesa owner requires special authorization to harvest trees for firewood.

The net benefits (in terms of CI_{bp}) of the holm oak facilitated natural regeneration scenario are slightly sensitive to variations on real discount rate. The facilitated holm oak natural regeneration scenario would be the preferred option for a landowner that demands an interest rate lower than 2 % from this investment scenario (Fig. 9.10). Discount rates lower than 2 % seem to be far from the rates that dehesa and other Mediterranean oak woodland owners use for discounting the stream of future expected private capital incomes from silvopastoral uses and private amenity consumption (Ovando et al. 2010).

Total income NPV indicators are less relevant for a dehesa landowner, but may be a key factor for designing forest conservation policies, since employment

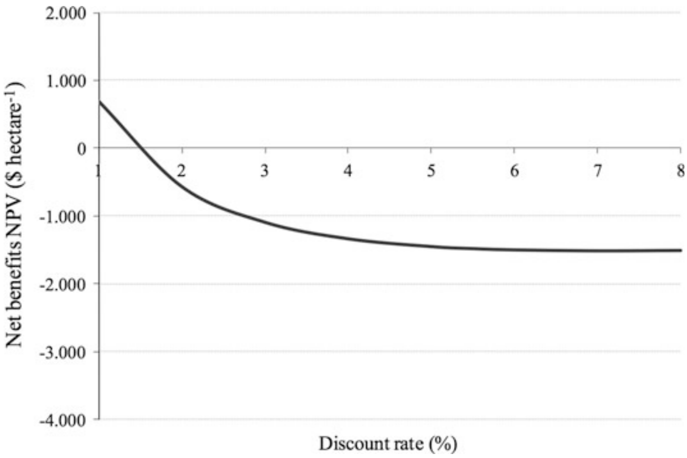

Fig. 9.10 Sensitivity of net benefits at basic prices, which includes subsidies net of taxes on products, of facilitated holm oak natural regeneration investment to discount rates

generation is one of the aims of European Common Agricultural Policy reforms. Facilitating natural regeneration of an aged holm oak stand delivers higher labor demand (Table 9.1) and labor incomes that offset the negative benefits of the present value of private capital incomes (Table 9.3).

9.3 California's Silvopastoral Management System

Silvopastoral management of oak woodlands in California relies on tree, forage, and livestock management to produce diverse economic and environmental values. Silvicultural, range production, and livestock models exist to assess silvopastoral management. The general approach develops an optimal control model to link biological, environmental, and economic components. The objective function is to maximize discounted net value by landowners over a planning horizon for livestock, firewood harvest, and fee hunting enterprises. Equation (9.12) below shows the general framework for this model, based on forage production models, oak growth models, and hunting revenue models (Standiford and Howitt 1992, 1993).

$$\max NPV = \int_{t=0}^{T} e^{-rt}\{WR_t(WDSEL_t) + HR_t(WD_t, HRD_t, exog.) + LR_t[HRD_t, CS_t, FOR_t(WD_t, exog.)]\} \tag{9.12}$$

such that:

$$\dot{WD} = f(WD_t, exog.) - WDSEL_t \qquad \text{(equation of motion for oaks)}$$

$$\dot{HRD} = G(HRD_t, exog.) - CS_t \qquad \text{(equation of motion for livestock)}$$

Initial Conditions: $WD_0 = INITWD$ and $HRD_0 = INITHRD$ where WD and HRD are the stock of wood volume and livestock numbers (cows); WR, HR and LR are the net revenues of firewood, hunting and livestock respectively; WDSEL is the volume of firewood sold and CS is a vector of the classes of livestock sold; FOR is the forage quantity available by season; r is the interest rate; and exog. are exogenous site factors (soil productivity, annual rainfall and temperature).

Solving this equation with existing prices and climatic data shows that in the last decade, the optimal solution was for landowners to completely clear the oak trees on their property because of the low growth rates of the trees, and the reduced forage production under tree canopies. This represents a "normative" approach to making recommendations to landowners on a maximum return from management of their oak woodlands.

However, these models did not reflect the actual behavior of oak woodland managers during this time period. Scenarios calculated for the early 1990s in California concluded that markets at that time would lead landowners to clear their oaks to increase forage yield for livestock production (Standiford and Howitt 1992). Although common in the 1940s–1970s, this behavior was actually rare in the nineties, contradicting the prediction of the model (Standiford et al. 1996).

These normative models have the drawback of omitting a landowner's amenity value from oak stands. To more realistically model landowner behavior in the current market, policy and climatic regimes, a positive mathematical programming (PMP) approach (Howitt 1995) was used to derive missing elements of the true costs and returns of oak harvest and retention for landowners. The dynamic optimization model is enhanced with a constraint for actual landowner behavior. The actual amount of firewood harvest and tree removal by landowners (Bolsinger 1988) was a constraint added to the model, and recalculated incorporating the actual behavior. The shadow prices derived from the behavior constraint represents the marginal benefit of retaining trees. That value was integrated to calculate a "hedonic" quadratic cost function for account for the apparently negative utility to landowners from overcutting oaks on their property.

Figure 9.11 compares firewood stumpage price to the "apparent" hedonic price. The difference between the two curves represents the "cost" of overcutting firewood, or the private amenity consumption value of retaining trees. Figure 9.12 shows the trajectory of optimum oak cover of the normative model, excluding the hedonic cost, and the positive model, which is calibrated to actual producer behavior.

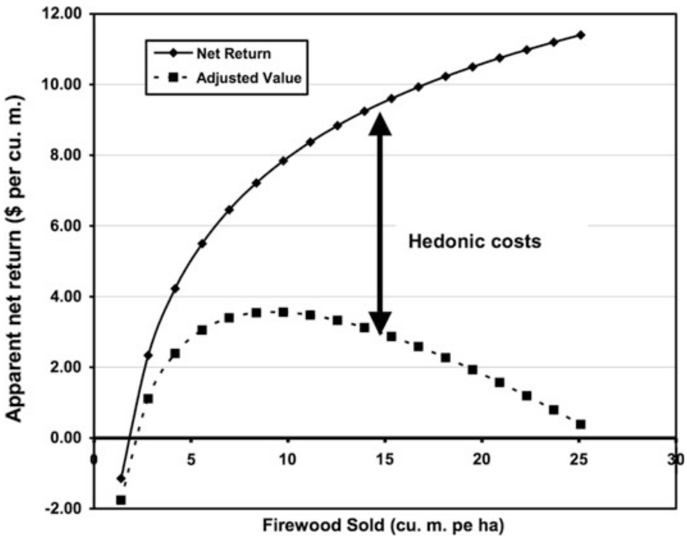

Fig. 9.11 Net firewood return per cubic meter as function of amount of wood harvested (reproduced from Standiford and Howitt 1992)

9.3.1 Commercial Production from Woodlands

A positive mathematical programming approach was used to model the trajectory of oak canopy cover, firewood harvest, and cattle stocking for different risk and land productivity conditions (Standiford and Howitt 1992). Figures 9.13 and 9.14 shows the contribution of the three major commercial enterprises to total net

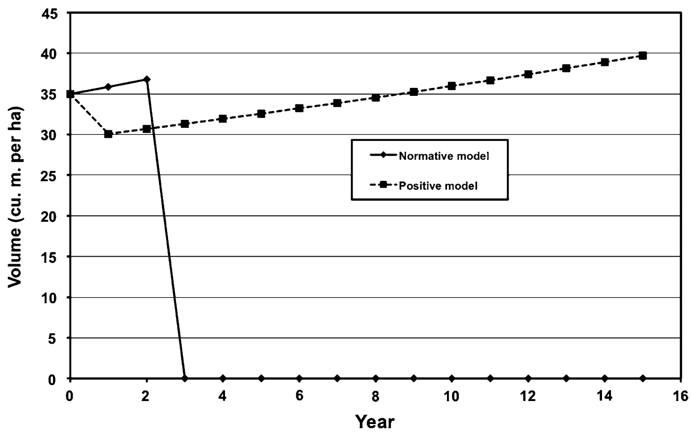

Fig. 9.12 Comparison of positive versus normative solutions to oak silvopastoral model

Fig. 9.13 Stacked firewood on a ranch in Tulare County, California, where there is a commercialized program marketing oak firewood (Photograph by M. McClaran)

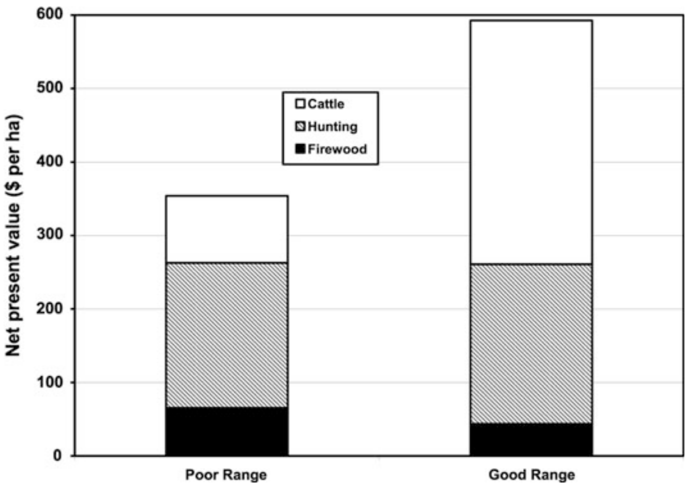

Fig. 9.14 Net present value (*NPV*) of California oak woodlands from various commercial enterprises on poor, or low productivity grazing land, and good, or high productivity grazing land (Standiford and Howitt 1993)

present value for an oak landowner with an initial condition of 30 percent oak canopy and a risk factor assuming that a loss can be tolerated in one year out of ten for a high and low productivity forage production area (Standiford and Howitt

1993). Fee hunting is an important enterprise, contributing 40–70 percent of total woodland value. Firewood, the only major wood product on California's oak woodlands, has low value compared to cattle or hunting enterprises. The marginal value of retaining oak tree cover for hunt club habitat often exceeds the marginal value of the extra forage or firewood harvest value resulting from tree harvest (Standiford and Howitt 1992). The model shows diversification of silvopastoral enterprises reduces tree harvesting and cattle grazing.

The model was evaluated for different risk scenarios for landowners, using a Cooper-Charnes chance-constrained approach (Charnes and Cooper 1959). In general, the higher the risk aversion, the more likely that firewood harvest would be relied on to reduce the probability of economic loss during low livestock price years, or poor forage production years. The capital value of the trees is a hedge against years with low livestock profitability. Inclusion of a risk term shows that firewood harvest and livestock grazing intensity both increase. Policies reducing landowner risk, such as a subsidized loan program during poor forage production or low livestock price years, might reduce the need to cut the trees for an infusion of capital (Standiford and Howitt 1993).

9.3.2 Tree Growth and Modeling

The approach used in the silvopastoral model described above was a whole stand oak growth model, based on 81 sample plots with 1,013 trees, located in seven different geographic regions throughout California oak woodlands (Standiford and Howitt 1988). This model derived a site index relationship for oaks on rangelands based on height and index diameter, rather than height-age relationships because of the difficulty in determining oak age. It also developed a simple basal area growth model for different initial stocking levels by site class. The model also provides correlations between basal area stocking and overstory canopy cover percent and tree height, as well as a site index relationship.

Another promising modeling approach for future silvopastoral modeling in California uses a distance independent, individual tree model (Standiford 1997). This approach provides an opportunity to model stand structure changes over time, with different thinning prescriptions. Stand structure changes can also incorporate coppice management, using the relationships derived in McCreary et al. (2008) and Standiford et al. (2010a, b). The probability of natural seedling regeneration can also be incorporated into these models (Standiford et al. 1997).

The USDA Forest Service supplemented its National Forest Inventory, focused on commercial forestlands, to include oak woodlands in the 1980s. The first report on the growth, harvest, regeneration status and mortality of the series of permanent plots on California oak woodlands was reported in Bolsinger (1988) and formed the basis for the positive programming approach described above (Standiford and Howitt 1992). The series of plots was expanded in the past decade to provide a more robust statistical survey of the state, with additional emphasis on wildlife habitat elements such as woody debris and snags, and exotic diseases such as Sudden Oak Death and pests such as the Golden Spotted Oak Borer (Waddell and Barrett 2005). The data from the U.S. Forest Service's Forest Inventory and Analysis unit can be used for additional calibration of actual landowner behavior.

Additional work on tree growth can be derived from controlled thinning experiments. Almost 20 years of stand development has been evaluated for three thinning levels for coast live oak (*Q. agrifolia*) throughout the Central Coast of California (Bonner et al. 2008). Over 15 years of stand structure change, sprouting, and acorn production have been measure for three thinning levels for blue oak (*Q. douglasii*) and interior live oak (*Q. wislizenii*) in the southern Sierra Nevada (Standiford et al. 2010b).

Ecologically based state and transition models have also been derived for various oak woodland cover types (George and Alonso 2008). These provide probabilities of different ecological pathways with different management and disturbance regimes. This approach can link tree cover, range productivity, and other vegetation species together, and provide input to economic and management models.

9.3.3 Incorporating Other Products of Silvopastoral Management

Cattle production, firewood harvest and fee hunting are the products currently dominant in California's silvopastoral management system. The models described above can be expanded to include other emerging markets as additional information on values and management costs are derived.

California has an emerging market for biomass energy, mainly using cogeneration facilities throughout the state. There have been opportunities for utilization of solid wood for cogeneration through various incentive programs (BIWG 2006). The overall wood volume from oak woodlands is substantially lower than on commercial conifer forestlands, which are only break-even at best at this time. Delivered wood prices are currently quite low, with high transportation costs.

Most California livestock production on oak woodlands is from cow-calf operations, with the sale of calves as the primary economic product (Standiford and Howitt 1993). These markets have been subject to extreme variability. There has been interest in evaluating value-added cattle products, with expanding demand for grass-fed beef and new meat packing facilities proposed to utilize grass-fed cattle. There has also been an interest in utilizing more stocker operations to manage the risk of annual forage fluctuations resulting from rainfall and temperature variability. Several studies point to the possible markets for these new livestock management and marketing strategies (Harper et al. 2005; Blank et al. 2006).

With the passage in 2006 of California's Global Warming Solutions Act (Assembly Bill 32) by the Legislature, the state set limits on greenhouse gas (GHG) emissions (ARB 2006). The law reduces GHG to 1990 levels by 2020–a reduction of

30 %–and another 80 % reduction by 2050. The new law establishes a cap-and-trade program to develop markets designed to encourage the sequestering of carbon. Preliminary analysis of the implications for oak woodlands showed that only $0.70 per hectare per year for central Sierra Nevada oak woodlands based on current markets is expected (Forero et al. 2010). However, as the implications of AB 32 for California's economy develop, the prices for sequestering carbon in oak woodlands may increase, and create new market opportunities for silvopastoral management.

9.4 Synthesis and Conclusions

These two silvopastoral modeling efforts in the Spanish dehesa and California oak woodlands reveal the important linkage of multiple outputs with realistic cost and return data. For the Spanish dehesa, silvopastoral modeling indicates that even if natural oak regeneration is 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 maintain future options for providing commodities and amenities for future generations. Long-term holm oak dehesa conservation may depend on implementing accurate compensation schemes, since private landowners are often unable to accept the short-term cash losses required to invest in dehesa regeneration. This work gives insights into the income losses that private owners may incur from natural oak regeneration treatments and grazing restrictions. We strongly suggest that 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 and Díaz 2008), which would simultaneously help mitigate long-term biodiversity loss (Chap. 8) and potentially boost landowner amenity and financial benefits from dehesa improvement and afforestation.

For California oak woodlands, the modeling effort shows the importance of incorporating actual landowner behavior into findings derived from current cost and return data. Landowners do receive value from maintaining certain levels of oak stands, and any policy analysis needs to carefully take this into account. Enhancements in modeling efforts are possible as the interrelationships between the various products from silvopastoral systems become better understood. In addition, new markets are anticipated, especially for ecosystem services and carbon sequestration, which will create new opportunities for sustainable silvopastoral management outcomes.

Acknowledgments The investigation carried out in dehesas is a contribution to the project "Análisis prospectivo de las rentabilidades social y privada de las forestaciones de encinas y alcornoques del periodo 1994–2000 en el marco del Reglamento 2080/92 (AREA)", supported by funding from the BBVA Foundation. The authors thank an anonymous referee for reviewing an earlier version of the manuscript.

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