AN ENVIRONMENTAL ECONOMIC ANALYSIS OF WILLOW SRC PRODUCTION

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ABSTRACT

It is anticipated that biomass 'energy crops' will become increasingly important as a carbon-neutral energy source in the light of international commitments to reduce greenhouse gas emissions. In this paper we theoretically model short rotation coppice (SRC) biomass production and empirically apply this model to the case of SRC biomass production in the UK. An environmental economic model of site value maximising SRC biomass production is developed from existing forest economics literature in the 'Faustmann' tradition. The contribution made by external, non-timber benefits to 'social' site value is assessed, and potential for divergence between private and social value maximising strategies is identified. Case study data are drawn from the first commercial-scale willow SRC production to be established in the UK. Model results show good agreement with commercial practice.

Keywords: Biomass energy crops, Faustmann formula, non-timber benefits, short rotation coppicing.

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INTRODUCTION

Existing forest economics literature focuses on trees for timber production (e.g. Faustmann, 1849; Samuelson, 1976; Chang, 1998). An emerging issue is that of trees for biomass energy generation. A key challenge for future forest economics is to adapt or extend existing theoretical frameworks to apply to new forest production and policy issues. This paper looks at the theoretical application of the 'Faustmann' timber production model to the case of SRC biomass pro-

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duction and presents the results of an empirical application of this model to commercial biomass production in the UK.

Under the Kyoto Climate Change Protocol, the European Union is committed to reducing emissions of greenhouse gases to 8% below 1990 levels by 2010. Also, under the 1985 Helsinki Protocol, the UK has undertaken to reduce SO_2 emissions to 30% of their 1980 level by 2005. Electricity generation from renewable energy sources is set to play a significant role in achieving these objectives by displacing fossil fuel-based generation which is a major source of greenhouse gas and acid rain precursor emissions (Sedjo *et al.* 1995)

Biomass 'energy crops' and wind energy are the renewable energy sources best positioned to make a substantial contribution to UK renewable generating capacity in the short to medium term (ETSU 1994). Willow (*Salix* spp.) and poplar (*Populus* spp.) are the most viable SRC biomass energy crops being developed in the UK (Brent, 1998). SRC biomass is harvested repetitively as a sequence of short, rapid, growth stages. Atmospheric carbon is sequestered when the biomass grows and is released again when the crop is burnt to produce energy. The overall growth and combustion cycle is 'carbon neutral' so electricity generation from SRC biomass makes no net contribution to greenhouse gas emissions (Patterson, 1994). Wood has negligible sulphur content so minimal SO_2 is emitted during combustion, and emissions of nitrous oxides (NO_x), also acid rain precursors, can be controlled by combustion technology, (ARBRE, 1998).

Trial-scale development of willow and poplar SRC in the UK showed promising results (Stenhouse & Beale, 1997). In 1994 a contract was awarded to the Arable Biomass Renewable Energy Consortium (ARBRE) to develop the UK's first commercial scale willow SRC-fuelled electricity generating station. Construction began on the ARBRE generating station in North Yorkshire at the end of 1998 and is scheduled for completion by late 1999, with the generating plant coming fully online by mid-2000. Successful commercialisation of electricity generation from willow SRC should see biomass making a significant contribution to UK energy supply in the future.

The ARBRE plant will produce 10MW of electricity using a Biomass Integrated Gasification Combined Cycle (BIG-CC) generating unit (ARBRE, 1998). Willow SRC fuel for the ARBRE plant will be supplied from SRC sites on surrounding farmland. Farmers enter into 19-year long fuel supply contracts with ARBRE, based around a willow SRC coppice stage duration time of 3 years. 2,000 ha of willow SRC are required to provide continuous fuel supply.

This paper develops a Faustmann type environmental economic model of SRC biomass production from the perspective of the private, profit maximising firm. Following Hartman (1976) this model is extended to include a number of non-market environmental benefits. This approach allows the potential divergence between private and socially optimal outcomes for coppice cycle structure and duration to be examined, and site value to be assessed. The model is applied to the case of SRC willow production by ARBRE in the UK. A biological growth model for SRC willow in the UK is adapted from Swedish data. When the chosen non-market environmental benefits are taken into account, coppice duration times tend to lengthen and site value increases by a substantial amount compared with the private, profit maximising outcome.

Financial incentives are currently provided to assist willow SRC-based energy generation until operating scale increases, technology develops and costs reduce. Such policy intervention could also encourage socially optimal production and land-use decisions. The potential effectiveness of some forms of policy intervention in producing the socially optimal outcome are examined in this paper.

We begin by describing the adaptation of existing forestry economic models to willow SRC production. Then we provide the specific details of ARBRE's commercial application and briefly outline the design and structure of the specially-written simulation software. Results produced by the software model follow. Finally, we discuss the results and present our conclusions.

Appendix 1 provides a comparative static analysis of the coppicing model. Adaptation of Swedish willow SRC yield data to UK circumstances is described in Appendix 2.

THEORETICAL MODEL

Private, Profit Maximising Model

Much classical forest economics literature has focussed on the production of timber for industrial use on forest land. Analyses by Faustmann (1849), Samuelson (1976) and others have examined the problem facing the private owner of a forest stand who seeks to maximise wealth by selecting the optimum felling time, given knowledge of timber prices, costs, timber growth function and the discount rate. Coppicing-specific private ownership models have been presented by Medema & Lyon (1985) and Tait (1986). Hartman (1976) presented a framework which included the flow of value produced by non-timber forest benefits in a social formulation of the value maximisation problem. Calish, Fight & Teeguarden (1978) applied Hartman's technique to assess the overall social value produced by Douglas fir forests in U.S. north-west. A comprehensive summary of all aspects of the forest value maximisation literature, from both a private and a public perspective, is provided by Chang (1998), and is not repeated here. Faustmann's seminal model (1849) is briefly summarised below to set up later extensions.

The net present value (NPV) of a forest stand dedicated to a continual, repetitive sequence of timber production stages to a private, profit maximising, owner when timber production represents the financially optimal land use for the site, is;

$$NPV(T) = \left(\left(P \cdot g(T) - C_f\right) \cdot e^{-rT} - C_p\right) \cdot \sum_{j=0}^{\infty} e^{-jrT} = \frac{\left(\left(P \cdot g(T) - C_f\right) \cdot e^{-rT} - C_p\right)}{\left(1 - e^{-rT}\right)}. \quad (1)$$

where j is a harvest index, and biomass growth rate, $g(t)$ (tonnes/hectare), market timber price, P (£/tonne), felling costs, C_f (£/hectare), re-planting costs, C_p (£/hectare) and discount rate, r, are all assumed fixed.

NPV is a function of the chosen stage duration, *T*, and is equal to the net value of a single stage discounted back to the start of that stage, multiplied by the factor $1/(1 - e^{-rT})$ to allow for the perpetual sequence of rotations. The first-order condition for maximising $NPV(T)$ by choice of stage duration time, *T*, is;

$$P \cdot g'(T) = r \cdot \left(P \cdot g(T) - C_f\right) + r \cdot NPV_{\max} \tag{2}$$

i.e. the wealth maximising stage duration time is that for which the marginal benefit and marginal cost of delaying the harvest are exactly equal. The marginal benefit of delaying the harvest is the value increment provided by additional biomass growth. The marginal cost of delaying harvest comprises the opportunity cost of leaving the current stage biomass standing, and the opportunity cost of continuing to use the land for timber production rather than selling it (for its maximised value $NPV_{\max}$) and banking the proceeds. The *maximised* NPV of the land can be termed the 'Land Expectation Value' (LEV). This 'Faustmann formula' for LEV, and the NPV-maximising condition on stage duration time, are the basis from which specific coppice production models have been developed.

Medema & Lyon (1985) adapted Faustmann's analysis to economic optimisation of the coppicing process, where a stand is used for an infinite sequence of coppice cycles. Coppicing is a rapid, cyclic timber production system in which an initial planting is followed by a sequence of separate harvesting *stages* when above-ground biomass is removed. At stage harvest the root 'stool' is left in the ground to resprout, providing biomass growth for the next stage. The productivity of the stool generally decreases over time until it becomes economically advantageous to remove the old stools and replant, beginning a new coppicing *cycle.* A detailed account of coppicing is given by Wood Supply Research Group (1997). Figure 1 illustrates the coppice process and the nomenclature used here.

Medema & Lyon's analysis allows biomass market price, stage productivity, (η_s), stage duration time, and regeneration cost to *vary between stages*. Overall coppice cycle duration, (the sum of the separate stage duration times), and discount rate are still assumed fixed. Harvesting and main-

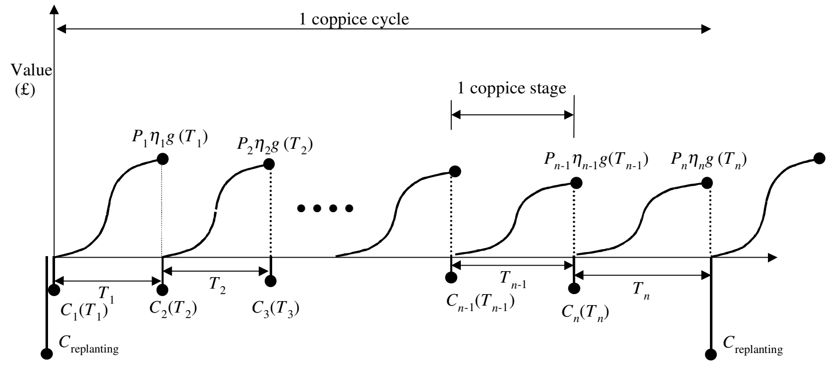

FIGURE 1. COPPICE CYCLE TERMINOLOGY.

tenance costs are amalgamated, with appropriate discounting, and referenced to the start of the stage concerned to give a 'stage' cost C_s as a function of growth stage duration time;

$$C_s(T_s) = \int_0^{T_s} M_s \cdot e^{-rx} dx + H_s\left(\eta_s \cdot g(T_s)\right) \cdot e^{-rT_s}, \tag{3}$$

where M_s represents maintenance costs and H_s harvest costs, which are assumed to increase as standing biomass increases.

Medema & Lyon's analysis uses the *complete coppice cycle* as its basic timeframe. NPV contributions from each stage are referenced back to the start of the complete coppice cycle and summed to produce overall cycle NPV. NPV maximisation becomes a two-part problem. The optimum time duration of each individual stage must be selected, and then the optimum number of stages must be included in the total cycle to maximise cycle NPV. Full details of the analysis and iterative optimisation process are given by Medema & Lyon (1985) and are not repeated here.

Tait (1986) adapts Medema & Lyon's approach for simpler iterative solution by *adjusting the 'decision point'* from the start of the complete cycle *to the point of harvest of each successive coppice stage* and by *isolating the initial site establishment cost, $C_{replanting}$,* as a separate 'stage' of zero time duration at the very start of the coppice cycle.

Chang's 'Generalised Faustmann Formula' (1998) provides a clear and concise analytical formulation within which Tait's coppicing framework can be expressed. Using Chang's nomenclature and Tait's framework, a site used for an infinite sequence of coppice cycles produces an LEV, in the general case for stage *s*, of ;

$$LEV_s = \left(P_s \cdot \eta_s \cdot g(T_s) \cdot e^{-rT_s} - C_s(T_s)\right) + e^{-rT_s} \cdot LEV_{s+1}. \tag{4}$$

Equation (4) expresses the LEV at the start of any stage, *s*, as a function of the value growth and costs associated with that stage, and the discounted LEV of the site at the start of the next stage, *s*+1. The LEV of the site, i.e. the maximised NPV arising from an infinite sequence of optimal decisions on stage duration time and stool replanting intervals into the infinite future, *varies between stages of the coppice cycle*. First order conditions on T_s for maximisation of LEV_s are;

$$\eta_s \cdot P_s \cdot g'(T_s) = r \cdot \eta_s \cdot P_s \cdot g(T_s) + r \cdot LEV_{s+1}, \tag{5}$$

i.e. the marginal benefit of continued biomass value growth just matches the marginal opportunity cost of the standing biomass plus the opportunity cost of reserving the site for coppice use for the next growth stage. Chang (1998) presents a comparative static analysis for his more general formulation of this problem in which he considers, separately, the impact of parameter changes in current and future stages on LEV and stage duration. A comparative static analysis specific to the coppice case is included in Appendix 1. Static results are derived for parameter changes applied to the current stage alone, and the impact of parameter change in both current and future stages simultaneously is discussed.

Tait's formulation presents selection of the optimum number of stages in a cycle, before replanting to renew the coppice stools, as a decision faced by the site owner after each stage harvest. After each stage harvest the site owner chooses either to continue with the existing coppice stools for one more growth stage, or to remove the old stools and replant with new ones to start a whole new coppice cycle. This decision is made on the basis of the site LEV delivered by the two options, LEV_s and $LEV_{replanting}$, where;

$$LEV_{replanting} = LEV_1 - C_{replanting} \tag{6}$$

i.e. LEV of site viewed from start of first stage minus the cost of replanting.

Equation (4) is a basic recursive relationship from which the optimum structure of the coppice cycle can be determined by computer iteration. LEV_{s+1} is merely a number. If it can be estimated by some means then a value of T_s which maximises LEV_s can readily be calculated. The better the estimate for LEV_{s+1}, the better the value for T_s which will be produced.

The backwards recursion process seeks to calculate an LEV_s-maximising value of T_s for each stage in the coppice cycle. The first iteration cycle utilises an arbitrary set of initial guesses for the set of LEV_{s+1} values to select a set of LEV_s-maximising stage duration times (T_1, T_2 etc). The LEV_s values produced using these stage duration times then form the LEV_{s+1} values for the next stage of iteration, and so on until the iteration converges on a fixed set of LEV_s values.

The timing of the replanting decision is easily incorporated within the iterative loop. Mimicing the site owner's decision process, the calculated LEV_s value for each successive stage is compared with $LEV_{replainting}$, (see Equation (6)). If $LEV_{replanting}$ exceeds the calculated LEV_s for the proposed next stage in the existing cycle then it is advantageous to replant in preference to persevering with the existing coppice stools for one more stage. This process is illustrated in Figure 2.

Willow SRC Biomass Growth Function

An extensive yield study of willow SRC in the UK is currently being undertaken by the UK Forestry Commission (Armstrong, 1997). Full results from this work are not yet available, although some initial findings are about to be released (Armstrong, *forthcoming*). The Wood Supply Research Group's '*Short Rotation Forestry Handbook*' (1997) presents a comprehensive set of results from willow SRC yield trials in Sweden. A substantial amount of willow SRC research has also been undertaken in Finland (Hytönen *et al.,* 1995; Hytönen, 1996). Readily available Finnish data did not however include details of the willow SRC growth function, or details of the

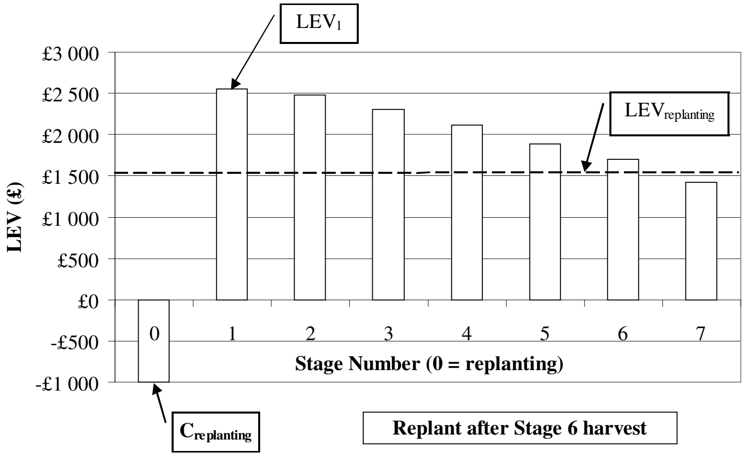

FIGURE 2. THE REPLANTING DECISION.

productivity reduction between successive coppice stages. These data were provided for Swedish willow SRC. The Swedish results have therefore been adapted to suit UK cultivation practice and climatic conditions to produce a yield relationship for use in this study. The adaptation is described in detail in Appendix 2.

In an even-aged, high density, stand of a managed tree species the main process regulating growth is intra-specific biological competition. Willow SRC yield (per hectare) may therefore be approximated by a logisitic growth curve which is used extensively in biological analysis. A logistic representation of biomass yield, g, as a function of time is (Mead & Curnow, 1983);

$$g(t) = \frac{B_{\max}}{\left(1 + e^{(a-k \cdot t)}\right)} \quad \text{or} \quad \frac{dg}{dt} = k \cdot g(t) \cdot \left(\frac{B_{\max} - g(t)}{B_{\max}}\right). \tag{7}$$

Early growth is initially unlimited by resource availability and proceeds exponentially at a rate governed by k. As growth continues resource limitations becomes apparent and the growth rate reduces, tending to zero as the maximum biomass 'carrying capacity' ($B_{\max}$) is reached.

Social Perspective

Additional service flows associated with timber production, such as wildlife habitat provision, water run-off filtration, recreational amenity provision etc. produce tangible benefits over time. A full social valuation of land used for timber production should include the net present value of benefits produced by all non-timber value flows as well as the net market revenues produced by timber sales. Hartman (1976) describes a method by which external, non-timber benefits can be included in a Faustmann-style analysis. Strang (1983) extends Hartman's analysis to include 'corner solutions' to the benefit maximisation problem in which the optimal strategy is to leave old growth forests standing indefinitely to capture the flow of non-timber benefits they provide.

Calish, Fight & Teeguarden (1978) were the first to apply Hartman's form of analysis. They considered Douglas fir (*Pseudotsuga menzeisii*) production in north-western USA and assessed the financial contribution to 'social' site value from external, non-timber benefit flows. Their results showed that non-timber values could contribute up to 75% of site 'social' LEV, under a modelling scenario which employed 'high but plausible' unit valuations for non-timber benefits.

Non-timber values can easily be included in Tait's recursive coppicing model using Hartman's approach since non-timber value flows, suitably discounted and piece-wise integrated, contribute to the net present value of the current stage. Thus the recursive coppicing model for site LEV including a representative non-timber benefit becomes;

$$LEV_s = \left[\left(P_s \cdot \eta_s \cdot g(T_s) \cdot e^{-rT_s} - C_s(T_s) \right) + \int_0^{T_s} V_{ntb}(x) \cdot e^{-rx} dx \right] + LEV_{s+1} \cdot e^{-rT_s}, \quad (8)$$

where $V_{ntb}(t)$ represents the flow of value derived from a particular non-timber source, (£/week). Biomass market price, costs, non-timber values, biomass productivity and biomass growth rate, can all vary between different stages of the coppice cycle. Consequently, *optimal stage duration times and site LEV can vary through the coppice cycle*. Overall cycle length, (the sum of the individual stage duration times), and discount rate remain fixed throughout the analysis.

Non-market Benefits

Willow SRC provides habitat for various flora and fauna. Game Conservancy Council data (DTI, 1994-b; 1994-c; ETSU, 1995) enables the functional form of the benefit flows associated with birds, butterflies and ground flora to be estimated as a function of stage duration time.

Birds are attracted to willow SRC in considerable numbers. Songbird abundance and diversity increases with shoot age, reaching a peak after 3 years and then declining (DTI, 1994-b). An inverse quadratic model of the form

$$V_{bd}(t) = S_{bd} \cdot \frac{t}{\alpha + \beta \cdot t + \gamma \cdot t^2}, \ (\textit{Bird Value Flow}) \qquad (9)$$

where S_{bd} is an overall scale factor is used to model the flow of value provided by birds in willow SRC.

Butterflies are only found in large numbers within the body of the willow SRC plantation in the first year after stage harvest, being mainly confined to headlands surrounding the site or rides through the crop thereafter. Relative butterfly abundances in the various parts of a willow SRC plantation (ETSU, 1995) and estimation of the percentage of a typical site area occupied by headlands, rides and the willow crop suggests an inverse exponential model for the flow of value provided by butterflies,

$$V_{bf}(t) = S_{bf} \cdot e^{-t/\tau_{bf}}, \ (\textit{Butterfly Value Flow}) \qquad (10)$$

where S_{bf} is an overall scale factor. τ_{bf} is the time-constant governing the rate of decay of butterfly value flow with coppice stage duration time.

Woodland coppice ground flora is well adapted to thrive beneath the coppice canopy without posing a competitive threat to the coppice trees. It provides habitat for a wide range of beneficial insects and suppresses annual ex-arable weeds with minimal impact on biomass growth (DTI, 1994-b). Ground flora is damaged by herbicide application after site preparation or harvest, but develops thereafter, increasing in volume and diversity as the crop ages. An inverse linear model

$$V_{gf}(t) = S_{gf} \frac{t}{\alpha + \beta \cdot t}, \ (\textit{Ground Flora Value Flow}) \qquad (11)$$

where S_{gf} is an overall scale factor is used to approximate the flow of value produced by beneficial coppice ground flora.

Riparian filter zones provide valuable environmental services such as filtration of nitrogen/nitrates, phosphorus and pesticides/herbicides from agricultural run-off, soil stabilisation and ground water recharge. Edwards *et al.* (1998) indicate that the flow of riparian benefits from willow SRC will rise relatively rapidly as the crop root stocks grow. An appropriate functional form to estimate riparian benefit flow is therefore;

$$V_r(t) = S_r \cdot \left(1 - e^{-t/\tau_r}\right), \ (\textit{Riparian Benefit Flow}) \qquad (12)$$

where S_r is an overall scale factor. τ_r is the time-constant governing the rate of increase of riparian benefit flow with coppice stage duration time.

Unlike a seed-producing arable crop, willow SRC can tolerate a substantial level of pest or disease damage before a significant reduction in revenue occurs, (Tucker & Sage, 1999). Rabbit grazing at the establishment stage or later foliage damage by chrysomelid willow beetles (*Phyllodecta* spp.), or by willow rust fungus (*Melampsora epitea*) represent the main threats. Protection is provided by rabbit fencing and planting a mixture of at least 5 different willow clones on the same site (Tucker & Sage, 1999). Agro-chemical intervention against pests and diseases is not generally necessary. Arable crops, by contrast, require considerable on-going agro-chemical input. Wheat receives, on average, 8 applications of agro-chemicals per year (DTI 1994-a). Non-market benefits therefore arise from agro-chemical input reduction when land is converted to willow SRC from arable production. The resulting benefit flow is assumed to be proportional to the reduction in volume of agro-chemical applied, and the magnitude of benefit is assumed to be greatest at the time of application, declining thereafter.

The initial herbicide application to willow SRC site after harvest is taken to be equivalent to one of the 8 agrochemical treatments applied yearly to an arable crop. The resulting, cyclic, function representing the flow of benefits from agro-chemical input reduction is

$$V_{ag\text{-}ch}(t) = S_{ag-ch}\left(e^{-t/\tau_{ag-ch}}\right) \quad 6.5 \text{ weeks} < t \leq T_s \qquad \textit{(Agro-chemical}$$
$$= 0 \qquad 0 < t \leq 6.5 \text{ weeks} \quad \textit{Benefit Flow)} \tag{13}$$

where S_{ag-ch} is an overall scale factor. τ_{ag-ch} is the time-constant governing the rate of decay of agro-chemical benefit flow with elapsed time.

The total NPV contribution derived from non-timber sources in a given coppice growth stage, V_s, as a function of growth stage duration time, is therefore;

$$V_s(T_s) = \int_0^{T_s} V_{bd}(x)\cdot e^{-rx}dx + \int_0^{T_s} V_{bf}(x)\cdot e^{-rx}dx$$
$$+\int_0^{T_s} V_{gf}(x)\cdot e^{-rx}dx + \int_0^{T_s} V_r(x)\cdot e^{-rx}dx + \int_0^{T_s} V_{ag\text{-}ch}(x)\cdot e^{-rx}dx. \tag{14}$$

Inserting this composite non-timber NPV contribution, $V_s(T_s)$ into Equation (8) produces the recursive relationship, Equation (15), which is used for the case study analysis.

$$LEV_s = \left[P_s \cdot \eta_s \cdot g(T_s)\cdot e^{-rT_s} - C_s(T_s) + V_s(T_s)\right] + LEV_{s+1}\cdot e^{-rT_s}. \tag{15}$$

Land used for willow SRC production for the ARBRE project has almost exclusively been converted from arable crop production. The non-market environmental values associated with this transition, some of which have been described above, are generally beneficial. Transportation of the willow fuel from the growing sites to the generating plant will produce some combustion emissions and road traffic flows, but these will be offset against reduced agricultural machinery operations at the growing sites.

This analysis, whilst including certain 'social' elements in the form of non-timber benefits from willow SRC, is primarily financial or 'commercial' in outlook. For this reason the costs of displaced agricultural production, agricultural labour effects and the environmental issues surrounding a reduction in the use of fossil fuels for electricity generation are not considered further here.

CASE STUDY APPLICATION: ARBRE WILLOW SRC IN THE UK

In this section we apply the theoretical model to the case of willow SRC production for the ARBRE electricity generating station in North Yorkshire, UK. Based on a growth stage duration of 3 years, 2,000ha of willow SRC are required to supply fuel for ARBRE's generating station. Willow SRC plantations are being established on farm land which was previously used for arable crops within a 50 mile radius of the generating site.

Willow SRC Cultivation Practice in the UK

Common cultivation practices have been adopted for willow SRC production on contract to ARBRE. Best practice guidelines are based on significant experience of willow SRC cultivation in Sweden, where more than 16,000 ha were in production in 1997 (Danfors *et al.*, 1998), and in Finland (Hytönen, 1996), together with specific modifications for local conditions arising from UK research (Armstrong, 1997 & *forthcoming*; McCracken & Dawson,1997). Cultivation details quoted here are drawn from ARBRE (1998), Brent (1998) and from personal communication with Barbara Hilton, ARBRE's Fuel Supply Co-ordinator.

Preparation of the willow SRC site entails site clearance, ploughing or power harrowing to encourage root development, liming if necessary, erection of rabbit fencing around the perimeter to prevent grazing damage to the young shoots and herbicide application to remove annual weed competition. Un-rooted cuttings are planted in a double-row arrangement on the prepared site using a mechanical planter. Planting density is 15,000 cuttings per hectare. A mixture of 5 different willow clones is planted to increase resistance to pest and disease attack. ARBRE currently estimate willow SRC establishment costs to be in the range £2,000 – £3,000 /ha. The main components of establishment cost are erection of rabbit fencing, purchase of the cuttings and the planting operation itself. There is currently only one supplier of approved cuttings in the UK, and planting machinery is still undergoing development. In the longer term ARBRE hope that establishment costs will fall to between £1,000 and £1,200 /ha, (Barbara Hilton, ARBRE, personal communication).

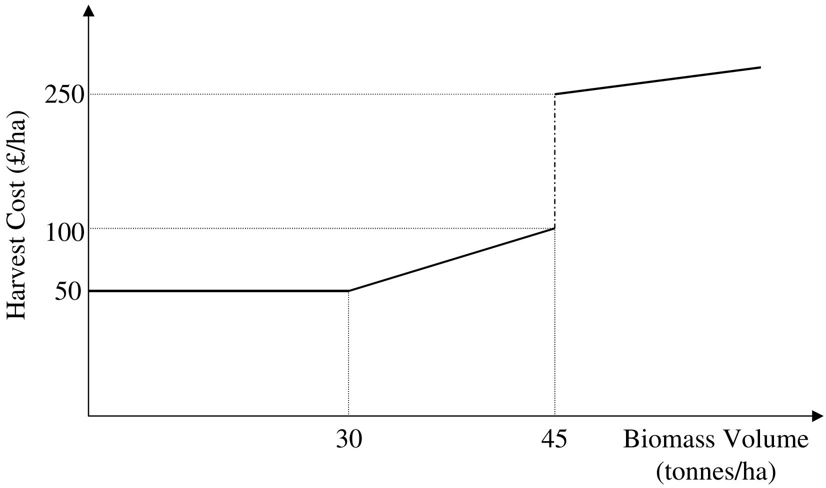

FIGURE 3. HARVEST COST FUNCTION.

The few stems produced during the first growing season after planting are cut back to ground level at the end of the first year to encourage true multi-stemmed coppice development. A further herbicide treatment may be required after cut-back. First-year cut-back has been priced at £20/ha (Brent, 1998), and herbicide application at £15/ha (ARBRE). An additional annual maintenance cost of £10/ha has been included to cover periodic inspection of the site.

Mechanised harvesters cut and bundle willow rods on the coppice site. Harvesting rate decreases once biomass volume exceeds a certain point, and, if biomass growth continues beyond mechanical harvesting capacity, manual felling will be required. For this analysis, the upper biomass volume limit of current mechanical harvesting capability is estimated to be 45 dry tonnes/ha, and the upper biomass limit for mechanised harvesting at full speed as 30 dry tonnes/ha. An assumed harvest labour cost of £75/day allied to these harvesting rates produces the piecewise-linear harvesting cost function of Figure 3[1]. ARBRE guarantee an index-linked price of £20/dry tonne for willow biomass. This fuel price is not backed by institutional support, and is therefore taken to be a realistic representation of the true market price of willow SRC fuel output.

[1] The piecewise linear harvest cost function, whilst analytically problematic, is a realistic representation of the cost implications of current limitations in willow SRC harvesting technology.

Willow SRC Yield Function

A logistic approximation to the willow SRC yield function for a planting density of 15,000 cuttings/ha under UK conditions is

$$g(t)=\frac{66}{\left(1+e^{(1.99-1.01\cdot t)}\right)}, \tag{16}$$

where $g(t)$ is biomass yield, (dry tonnes/ha), t is growth stage duration (years), and the parameters are estimated from Swedish data suitably adapted to UK conditions, (see Appendix 2).

The variation in productivity of willow SRC over successive growth stages in the same coppice cycle has also been studied in Sweden, (Wood Supply Research Group, 1997), where results indicate that productivity decreases during the later stages in a coppice cycle, falling to 53% of its maximum by the sixth growth stage. If the first stage duration is shorter than 5 years in total, (i.e. four years of harvestable growth after the first year cut-back), maximum productivity will not generally be reached until the second stage in the cycle. For a first stage duration of less than five years Swedish data suggests that first stage productivity will increase from 0% for the first year, (biomass from the first year cut-back is generally discarded), to 100% of the achievable maximum by the fifth year as the root stock becomes established.

Non-Market Benefit Flow Functions

Specific functional forms were constructed for each non-market benefit value flow function — birds, butterflies, ground flora, riparian and agro-chemical input reduction. The same method was adopted in all cases. Firstly parameter values (α, β, γ, τ_{bf}, τ_r, $\tau_{ag\text{-}ch}$) were selected for each non-market benefit value flow function to produce a value flow 'time profile' which matched the ecological and environmental research referenced in the preceding section. Secondly, each non-market value flow scale factor (S_{bd}, S_{bf} etc.) was used to adjust the magnitude of NPV contribution from each non-market source independently. For example, inserting the quadratic parameters α = 10.0, β = 0.005, γ = 0.00041 in the 'birds' benefit value flow function produces a rapid rise in instantaneous value to a peak after 3 years followed by a slow decline. The NPV contribution from 'birds' can then be adjusted by modifying S_{bd} whilst the time profile of the 'bird' value flow and the discount rate remained fixed.

Because of the difficulty in determining exact magnitudes for the value contribution arising from each non-market benefit, 'low' and 'high' non-market benefit valuation scenarios were used in the analysis. In the 'low' non-market benefit valuation scenario each individual non-market benefit was scaled to produce a NPV benefit contribution of £12/ha/year, (i.e. £180/ha NPV contribution from non-market values in total over 3 years, or roughly £1/ha/month from each non-market benefit – ignoring discounting). The 'high' non-market benefit scenario generated a NPV contribution of £52/ha/year for each non-timber benefit, (i.e. £780/ha total non-timber benefit contribution over 3 years, or roughly £1/ha/week from each non-market benefit).

For comparison, Willis *et. al.* (1995) quote payments of £60/ha/year offered to induce farmers to maintain 'conservation headlands' in arable cropland within the South Downs Environmentally Sensitive Area (ESA) in the south of England. Research by the Macaulay Land Use Research Institute (MLURI) into the Farm Woodland Premium Scheme in Scotland, (which encourages farmers to plant trees on farmland), concluded that a lower bound for the average private non-market benefit accruing to the farmer from planting woodland amounted to £258/ha/year, MLURI (1996).

A 4% discount rate was used throughout this part of the analysis. Thus, when the 'bird' value flow quadratic parameters are selected to produce the desired time profile of value flow and the discount rate is set at 4%, a 'bird' scale factor of S_{bd} = 0.047 produces a NPV contribution of £36/ha over 3 years.

Software Implementation

The willow SRC environmental economic model is implemented as a set of MATLAB®[2] script functions in the MATLAB® maths software environment. Individual rou-

[2] MATLAB® is a registered trademark of The MathWorks, Inc.

tines were written to calculate the market components of NPV (timber value and market costs) as functions of coppice stage duration time for a given set of parameters (timber price, establishment cost, harvesting cost etc.), assuming a willow SRC yield function as previously described. A reverse recursive optimising routine was then designed using Equation (15) as the basis for recursive iteration, optimising the number of growth stages per cycle and the duration of each individual growth stage to maximise LEV. The optimising routine was verified for the market-only situation by replicating Tait's (1986) results based on Medema & Lyon's (1985) case study. Non-market benefits were then introduced as an additional contribution to NPV in the manner already described. NPV contributions produced by the non-market benefit software routine were verified against separate spreadsheet calculations of NPV. Inclusion of non-market benefits is achieved without modification to the recursive optimising routine. The modelling software is confidently believed to operate correctly. Verification by comparison of modelled results with standard commercial practice is discussed in the next section.

Results

Results produced from the coppicing model using market data only are presented first, non-market benefits are then introduced. Trends within the results and the sensitivity of the outcomes to parameter change are discussed.

Results Using Market Values Only

Basic market data, together with the willow SRC yield equation and its associated productivity roll-off relationships, were applied to the coppicing model. The resulting site LEV values, optimum growth stage duration times and optimum overall coppice cycle structure are shown in Table 1. The site LEV values quoted for each growth stage are present valued to the start of the growth stage concerned, as indicated by Equation (4).

Contributions to (stage-start present valued) site LEV from coppice cycles far in the future are essentially identical, irrespective of the viewpoint. The relative timing of replanting expenditure and productivity-dependent

TABLE 1. 'REFERENCE POINT' MARKET-ONLY RESULTS.

Establishment Cost £1,000	Discount Rate 4%	
Stage Number	Site LEV (£/ha)	Stage duration time (years)
1	£2,555	4*
2	£2,480	3
3	£2,301	3
4	£2,119	4
5	£1,890	4
6	£1,698	4
6 stages per coppice cycle	*'Initial' LEV* (£/ha) £2,555	Cycle duration 22 years

* First stage duration includes the first-year cutback, so the number of years of growth harvested at the end of the first stage is one year less than the quoted first stage duration time.

biomass value returns from growth stages just ahead of the viewpoint does, however, influence (stage-start present valued) site LEV. Site LEV is thus somewhat viewpoint specific. As replanting expenditure approaches and biomass productivity reduces through the coppice cycle site LEV declines. The 4% discount rate data in Figure 4 show it is advantageous to replant after the sixth growth stage at this discount rate to restore site LEV to $LEV_{replanting}$ rather than proceed to a seventh growth stage with the existing stools.

The LEV at the start of the first coppice stage, LEV_1, is termed the '*Initial LEV*' and is quoted for the 'reference point' case in Table 1 as a representative figure against which sensitivity to parameter change can be assessed. The 'reference point' results correspond quite closely with ARBRE's 19 year coppice cycle contract for fuel production which comprises 6 growth stages each of 3 years duration, preceded by an initial year of growth leading to first-year cut back. The four year duration times for the final three growth stages of the coppice cycle predicted by the model are a consequence of productivity reduction in the later stages of the coppice cycle. Appendix 1 provides supporting analysis.

The '*Initial LEV*' value does not include the establishment cost, $C_{replanting}$, sunk in the project at the outset. The overall net present value of the optimal willow SRC coppice venture, viewed from the outset, is therefore (*Initial LEV* – $C_{replanting}$), i.e. $LEV_{replanting}$. It is reasonable

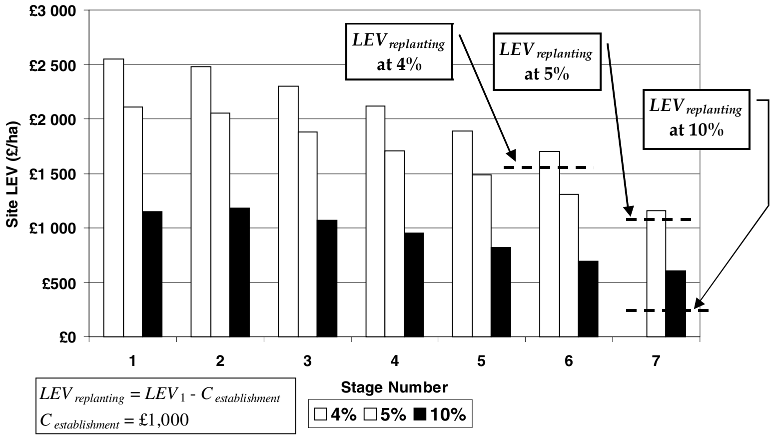

FIGURE 4. INFLUENCE OF DISCOUNT RATE ON COPPICE CYCLE DURATION.

to suppose that a 'commercial' decision to switch land use to willow SRC production will be made if this net present value exceeds that obtainable from other land use options. Conversely, land use will switch away from willow SRC again if the net present value position reverses, for example because of changing agricultural prices or subsidies. The nature of the replanting decision, (see Figure 2), ensures that $LEV_{replanting}$ is the lowest optimised net present value in the whole coppice cycle, and it is against this value that the net present value generated by alternative land uses should be compared.

Discount rate in the model was adjusted between 4% and 10%, with the other 'reference point' parameters unchanged. The results are shown in Figure 4.

Discount rate has a major impact on 'Initial LEV', as anticipated from comparative static analysis, (Appendix 1). Reduced 'Initial LEV' at high discount rates also acts to lengthen the overall coppice cycle by reducing $LEV_{replanting}$ which delays replanting investment as shown in Figure 4 and Figure 5 following.

Discount rate changes influence overall cycle construction by altering the number of stages in the cycle rather than by changing individual stage duration times. Comparative static analysis in Appendix 1 shows that discount rate changes in current and future growth stages exert conflicting influences on optimum stage duration time, leaving it unchanged overall.

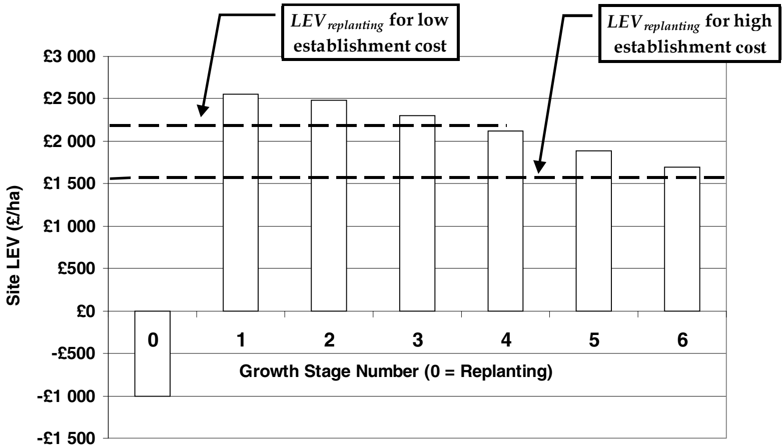

FIGURE 5. ESTABLISHMENT COST AND OPTIMUM NUMBER OF STAGES IN A CYCLE.

The 'reference point' market-only results of Table 4 used an establishment cost of £1000/ha, which is approximately the level to which establishment cost is expected to fall as planting technology develops[3]. Establishment cost currently lies between £2,000 and £3,000/ha, but can be offset by an establishment grant of £1,000/ha under the 'Location Supplement' to the UK Forestry Commission's Woodland Grant Scheme, (Forestry Commission, 1998-a; 1998-b). The influence of varying establishment cost between £500/ha and £3,000/ha in the market-only case is examined below. The results are summarised in Table 2 and Figure 5.

Establishment cost exerts only a modest influence on '*Initial LEV*'. This influence acts by changing site LEV at the point of replanting. Replanting occurs when $LEV_{replanting}$, i.e. $(LEV_1 - C_{replanting})$, exceeds LEV_{s+1}. LEV_{s+1} here is the optimised present value of the site viewed from the start of what would have been the next stage of the current coppice cycle if replanting had not occurred. The current value of the financial benefit produced by the decision to replant is $(LEV_{replanting} - LEV_{s+1})$. The contribution which this benefit makes to '*Initial LEV*', i.e. the present value of this financial benefit at the start of the first ever coppice cycle, is therefore

[3] Barbara Hilton, ARBRE, personal communication.

TABLE 2 INFLUENCE OF CHANGING ESTABLISHMENT COST.

Discount Rate 4%

Establishment Cost: *Varied between £500/ha and £3,000/ha*

Establishment Cost (£/ha)	Number of Stages per Cycle	*'Initial' LEV* (£/ha)	$LEV_{replanting}$ (£/ha)	Cycle duration years
£500	5	£3,070	£2,570	18
£1,000	6	£2,554	£1,554	22
£1,500	10	£2,416	£916	42
£2,000	>18	£2,371	£371	>78
£2,500	>18	£2,371	-£129	>78
£3,000	>18	£2,371	-£629	>78

$$\left(LEV_{replanting} - LEV_{s+1}\right) \cdot e^{-rT_{cycle}}, \tag{17}$$

where T_{cycle} is the duration of the complete coppice cycle and r is the discount rate.

Thus where the coppice cycle duration is long, 'Initial LEV' values are essentially unaffected by changes in establishment cost. The results in Table 2 shows this effect clearly.

Despite having only a modest influence over 'Initial LEV', establishment cost exerts a very strong influence on coppice cycle duration and on the land use switching decision. Low establishment cost reduces the optimum number of stages in the coppice cycle because restoration of LEV to $LEV_{replanting}$ by relatively low cost replanting investment, quickly becomes an attractive option once LEV begins to fall as a consequence of productivity reduction, (see Figure 5). When establishment cost is low, $LEV_{replanting}$ is high, making willow SRC production attractive compared with alternative land uses. When establishment cost is high the corresponding $LEV_{replanting}$ value is low and it is advantageous to prolong coppice cycle duration. Under these conditions, however, willow SRC production is unlikely to be the land use producing the highest net present value return.

Under 'reference point' conditions, when establishment costs exceed around £2,400/ha it is advantageous to persist with the original coppice stools even when produc-

TABLE 3. IMPACT OF NON-TIMBER BENEFITS ON SITE 'INITIAL' LEV AND CYCLE DURATION.

Establishment Cost £1,000	Discount Rate 4%	
Model Scenario	*'Initial' LEV* (£/ha)	Complete Coppice Cycle Duration (Years)
Market only	£2,555	22
'Low' NTB	£4,009	23
'High' NTB	£9,629	32

tivity decline in the latter stages of the cycle reduces site LEV below zero, (reference the $LEV_{replanting}$ figures in Table 2 and the decision mechanism shown in Figure 5). In this situation any alternative land use which produces positive net present value returns will be chosen in preference to willow SRC production at the outset.

Grant support towards establishment cost is an interim measure which will be removed once lower cost planting technology is developed. For this reason, an establishment cost of £1,000/ha, i.e. the level including available grant assistance, is used in subsequent analyses.

Results Including Non-market Values

Non-market benefits arising from the values associated with wildlife habitat provision, riparian 'buffering' of water courses and agro-chemical input reduction were introduced into the 'reference point' model. 'Low' and 'high' value scenarios for non-market benefits were investigated. Table 3 and Figure 6 show the results.

The optimised coppice cycle time and individual stage duration times produced with a 'low' level of non-timber benefit are almost identical to the market-only results. 'Initial LEV' increases by more than 56% above the market-only level however, when even only this 'low' level of non-timber benefits are included. Introducing a 'high', but still plausible, level of non-timber benefits changes the outcome considerably. Overall cycle time is lengthened by almost 50%, site 'Initial LEV' increases by a factor of 3.77, and the optimal duration of the early stages within a cycle increases markedly, (see Figure 6). These results suggest that considerable potential for divergence between private and social outcomes exists if the level of non-timber benefit provided by wil-

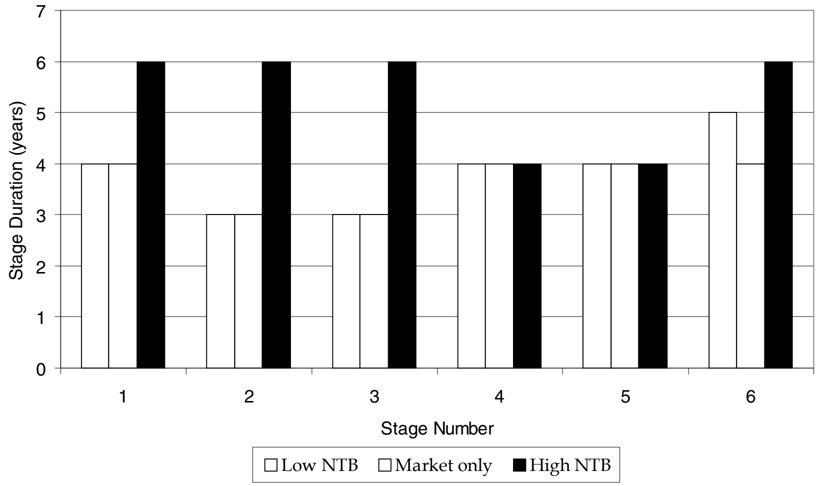

FIGURE 6. INFLUENCE ON NON-TIMBER BENEFITS ON GROWTH STAGE DURATION.

low SRC approaches the 'high' value scenario modelled here. If the 'low' value non-timber benefit scenario is closer to the true situation however then there appears to be little potential for private and socially optimal outcomes to diverge.

In summary, applying willow SRC case study data from the UK to the environmental economic coppicing model produces an NPV-maximising coppice cycle structure which is very similar to current commercial practice. Discount rate has been shown to be a strong influence on site 'Initial LEV', and also therefore on overall coppice cycle duration and on the land use decision, but to exert little influence on individual growth stage duration time. Establishment cost has been shown to influence coppice cycle structure and the land use decision strongly, but to influence site 'Initial LEV' to a much lesser extent. Potential for divergence between private and socially optimal coppice cycle designs has been shown to exist when a high, but plausible, valuation is placed on the non-timber benefits produced by willow SRC.

DISCUSSION AND POLICY IMPLICATIONS

Basic Trends in the Results

Agreement between the optimum prescription of the 'reference point' and current commercial willow SRC practice, as evidenced by ARBRE's fuel supply contract, suggests that the model provides a good approximation to the real world. In particular, the modifications which were made to the willow biomass yield function for UK conditions and cultivation practices appear to be reasonably realistic.

The structure of the optimised coppice cycle prescribed by the model is largely determined by the form assumed for productivity reduction through the cycle. The model prescriptions presented here are thus susceptible to change if subsequent willow SRC data indicate a different form of productivity roll-off under UK conditions. If the productivity reduction modelled here is realistic then it appears economically advantageous to extend the duration of later stages in the cycle.

Influence of Parameter Variation

Variations in productivity, discount rate and establishment cost have been shown to influence coppice cycle 'structure' and, to varying degrees, site 'Initial LEV'. Parameter changes act in accordance with the comparative static analysis of Appendix 1.

Chang's (1998) comparative static analysis for his 'Generalised Faustmann Formula' predicts that increasing the discount rate in the current stage decreases the optimum duration for the current growth stage (in true 'Faustmann' fashion), but increasing the discount rate in any future growth stage is predicted to increase the optimum duration of the current stage. The results presented here support these conclusions, *provided that the discount rate change is applied to either the current stage or to future stages*. When a discount rate change is applied to *both* current and future stages simultaneously then the effect on optimum duration time for the current growth stage is highly application specific. In the ARBRE case the conflicting influences of discount rate changes in current and future growth stages on the opportunity cost of delaying harvest cancel one another out almost entirely and stage duration times remain unaffected by discount rate changes.

Divergence of Social and Private Optima

Introducing a 'low' level of non-timber benefits into the model to obtain an indication of 'social' site LEV for willow SRC production produces a result which accords with Calish, Fight & Teeguarden's (1978) finding that non-timber benefits can make a considerable contribution to site LEV. Placing a 'high' valuation on non-timber benefits strengthens this conclusion. These results are, however, dependent on the functional forms assumed for the non-timber value flow functions. A useful extension of the work presented here would be to apply the 'implicit valuation formula' approach developed by Dole (1999) to derive lower bounds for the value of non-timber benefits required to produce changes in stage duration time and cycle structure of the magnitude predicted by the coppicing model.

Establishment Grant Incentive for Willow SRC Production

Establishment cost has been shown to exert a strong influence on cycle structure via the replanting decision. Establishment cost subsidy increases $LEV_{replanting}$ directly and also increases 'Initial LEV', but to a much smaller extent. This encourages uptake of willow SRC by increasing the net present value of willow production without distorting coppice cycle structure away from the market-only optimum. Excessive subsidy of establishment cost will act to shorten cycle time, moving cycle structure further away from the social optimum (Table 2, Figure 5 and Figure 6). Removal of the subsidy before the willow cutting supply market and planting technology have developed sufficiently to deliver the anticipated reduction in establishment cost could seriously reduce the amount of land which is converted to willow SRC production. Alternative land uses which deliver net present values in excess of the $LEV_{replanting}$ figures quoted against varying establishment cost in Table 2 would then be commercially preferred to willow SRC production. The current level of establishment subsidy undoubtedly encourages the production of willow SRC as a 'carbon-neutral', renewable fuel for electricity generation. This brings external benefits in greenhouse gas reduction etc. which have not been considered in this study.

Extension of the model to a 'social' framework which included additional external issues would make it more generally applicable as a policy analysis tool. Explicit analysis of the action of the establishment grant and 'set aside' payments together with other forms of subsidy, using the techniques outlined by Englin & Klan (1990), would also be useful and could be undertaken in the future.

An environmental economic model for the production of willow SRC biomass to fuel electricity generation has been developed. Market elements of the model are drawn from existing forest economic analyses of the 'Faustmann' type, building on the work of Faustmann (1849), Medema & Lyon (1985), Tait (1986) and Chang (1998). The model has been extended to include non-market benefits in the form outlined by Hartman (1976), applied in the manner of Calish, Fight & Teeguarden (1978).

The model is implemented by iterative simulation software and has been applied to the production of willow SRC biomass for the ARBRE willow-fuelled power station currently being constructed in the UK. A UK willow SRC yield function has been adapted from existing Swedish willow SRC yield data.

The results produced by the model show good agreement with current commercial practice. Growth productivity and discount rate parameter variation results support the use of Chang's 'Generalised Faustmann Model' (1998) as a simple and tractable analysis tool for forest economic analysis under changing conditions.

Including even a 'low' level of non-timber benefits in the simulation increases site value substantially. This accords with Calish, Fight & Teeguarden's (1978) findings on non-timber values in Douglas-fir stands in north-western USA. Private and social outcomes do not diverge significantly when a 'low' valuation is placed on the non-market benefits produced by willow SRC. Private and social outcomes do differ substantially, however, when non-timber benefits are valued more highly.

The current level of willow SRC establishment grant has been shown to increase site value and promote uptake of willow SRC production without shifting the optimum coppice cycle structure any further away from the social optimum than it already is under 'private' conditions. An excessive level of establishment grant could increase divergence between private and social outcomes, at least from the perspective of this study. Insufficient establishment subsidy, whilst the willow cutting supply market and planting technology are still developing, could seriously jeopardise willow SRC fuelled renewable energy generation by restricting fuel supply volume.

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Appendix 1

The coppicing model's fundamental recursive relationship is;

$$LEV_s = \left(P_s \cdot \eta_s \cdot g\left(T_s\right) \cdot e^{-rT_s} - C_s\left(T_s\right) + V_s\left(T_s\right)\right) \; + \; e^{-rT_s} \cdot LEV_{s+1}. \qquad \text{(A1.1)}$$

Site LEV, LEV_s, and duration time, T_s, are influenced by changes in biomass price P_s, stage growth productivity η_s and discount rate r.

First Order Impacts on LEV_s

Productivity: $$\frac{\partial LEV_s}{\partial \eta_s} = P_s \cdot g\left(T_s\right) \cdot e^{-rT_s}.$$

All terms are positive, so LEV_s falls as productivity decreases. Introducing a biomass yield-dependent harvest cost, $C_s(\eta_s, T_s)$, modifies this result to;

$$\frac{\partial LEV_s}{\partial \eta_s} = P_s \cdot g(T_s) \cdot e^{-rT_s} - \frac{\partial C_s}{\partial \eta_s}.$$

If higher productivity increases harvest cost then the overall influence of productivity on LEV_s depends on change in harvest cost relative to the change in biomass value yield. If the increase in harvest cost dominates then LEV_s will decrease. This would provide a strong incentive for improving in harvest technology.

Discount Rate : $\frac{\partial LEV_s}{\partial r} = -T_s \cdot P_s \cdot \eta_s \cdot g(T_s) \cdot e^{-rT_s} - T_s \cdot e^{-rT_s} \cdot LEV_{s+1}.$

All terms are positive. Thus LEV_s decreases as the discount rate increases.

Biomass Price: $\frac{\partial LEV_s}{\partial P_s} = \eta_s \cdot g(T_s) \cdot e^{-rT_s}.$

All terms are positive. LEV_s increases as biomass price rises.

INFLUENCES ON STAGE DURATION TIME T_s

The influence of productivity, price or discount rate change on stage duration time T_s is found by considering the f.o.n.c for maximisation of LEV_s.

$$\eta_s \cdot P_s \cdot g'(T_s) = r \cdot \eta_s \cdot P_s \cdot g(T_s) + r \cdot LEV_{s+1},$$

i.e. at optimum T_s the marginal benefit of biomass value growth just matches the opportunity cost of standing biomass plus the opportunity cost of maintaining the site in coppice production for the next stage of the coppice cycle.

Equation (A1.1) is of exactly the same form as Chang's (1998) 'Generalised Faustmann Formula'. Chang considers the impact of parameter change on the current stage and future stages separately and shows that increasing either of the opportunity cost elements, or decreasing intrinsic biomass value growth, rate reduces optimum stage duration time. Decreasing either of the opportunity cost elements or increasing biomass value growth rate lengthens optimum stage duration time. Because of the short overall cycle duration for willow SRC, changes in productivity, biomass price and discount rate have been applied to current and future stages simultaneously in this analysis. The consequences on T_s are application specific, but match Chang's predictions.

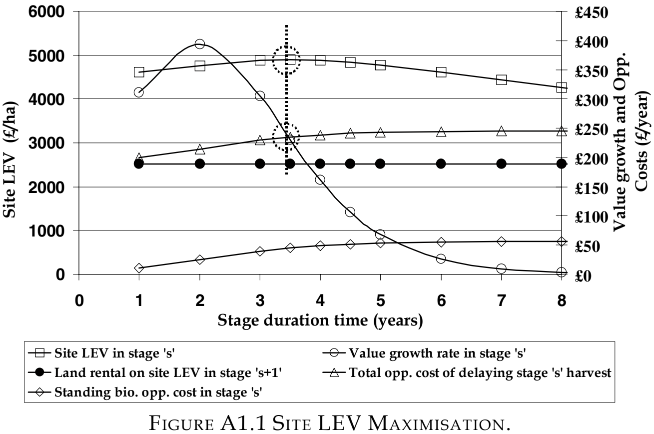

FIGURE A1.1 SITE LEV MAXIMISATION.

Figure A1.1 shows marginal benefits and costs at LEV_s maximisation for a stage within the overall coppice cycle using data from the ARBRE application. Near maximum LEV_s the marginal benefit of biomass growth and the total opportunity cost of delaying harvest exert conflicting influences on T_s. The largest component of opportunity cost element is site rental for the next stage, LEV_{s+1}. First order impacts of parameter change on LEV_{s+1} therefore exert a strong influence on optimal stage duration time T_s.

For example, productivity reduces as the coppice cycle proceeds. Falling productivity reduces the biomass value growth rate and the opportunity cost of the standing biomass. The first of these terms dominates, ceteris paribus (it is the steeper curve in Figure A1.1). If these were the only consequences of falling productivity, T_s would reduce. However, productivity decrease also reduces LEV_{s+1} and therefore the opportunity cost of maintaining the site in coppice production. This acts to increase T_s. In this application the site rental opportunity cost is the strongest term, so T_s increases as productivity decreases through the coppice cycle.

Increasing the discount rate does not affect biomass value growth but decreases LEV_{s+1} as a first order effect whilst also increasing both opportunity cost elements directly by multiplication. In this application these two effects almost cancel one another out and stage duration time is unaffected by modest changes in the discount rate.

Appendix 2

Swedish Willow SRC Yield Data

The circled data points in Figure A2.1 show averaged biomass yield for coppice growth stage duration times of between 1 and 6 years for the 5 top-yielding clones in Swedish willow SRC trials, (Wood Supply Research Group 1997, 'Swedish Production-Rotation Trial', Figure 1).

A good statistical fit with these data is provided by the cubic expression;

$$g(t) = 3.89 \cdot t + 2.59 \cdot t^2 - 0.28 \cdot t^3 \qquad r^2 \text{ (adjusted)} = 0.998 \qquad \text{(A2.1)}$$

If this paper analysed willow SRC in Sweden, then Equation (A2.1) could be used directly in the software model. However, a yield function for willow SRC grown under UK conditions and cultivation practices is required. The cubic approximation to the yield curve is unrelated to underlying biological or ecological parameters. A logistic form of growth equation links with underlying growth phenomena and provides a better starting point for modification to UK circumstances.

Equation A2.2 provides a good functional fit to the Swedish willow SRC data (Figure A2.1).

$$g(t) = \frac{66}{\left(1 + e^{(2.55 - 0.725 \cdot t)}\right)}. \qquad r^2\text{(adjusted)} = 0.985 \qquad \text{(A2.2)}$$

($g(t)$ in dry tonnes/hectare, growth stage duration t in years)

Adaptation of Swedish Yield Data to UK Conditions

The Swedish yield data relates to an initial planting density of 10,000 cuttings/ha. ARBRE's UK willow SRC sites are planted at an initial density of 15,000 cuttings/ha.

Kira's law of constant final yield under intra-specific competition (Begon *et al.*, 1998, p229) suggests that the increased planting density will produce a more rapid yield increase during the earlier stages of growth but will not result in a higher final yield. (More coppice trees are produced, each of a smaller average

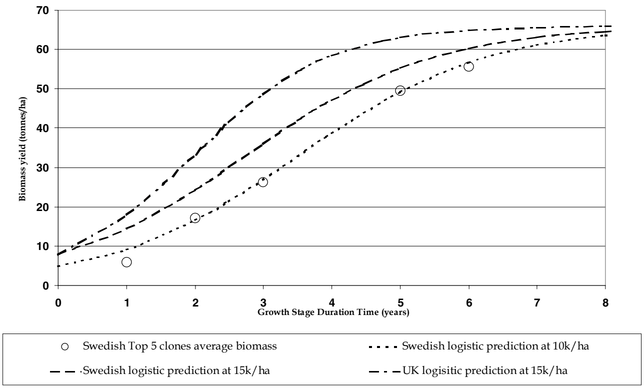

FIGURE A2.1 LOGISTIC YIELD CURVE ADAPTATION SEQUENCE FROM SWEDISH DATA.

size). Thus the carrying capacity term in the logistic equation (66) should not change because of increased planting density.

Early unrestricted growth should also be unaffected by the density increase, so the exponential parameter (0.725) should also remain unchanged. Yield during the intermediate stages would, however, be expected to increase at higher initial planting density. The logistic parameter (2.55) governs this part of the yield curve.

Armstrong (*forthcoming*) quotes 3 year harvest figures for top yielding willow SRC in the UK *planted at both 10,000 and 15,000 cuttings/ha*. This result enables the 3 year yield point to be scaled for the change in planting densities by adjusting the logistic parameter. The modified yield relationship becomes, (Figure A2.1);

$$g(t) = \frac{66}{\left(1 + e^{(1.99 - 0.725 \cdot t)}\right)}. \tag{A2.3}$$

Further adjustment is required to allow for the different growing conditions in Sweden and the UK at the same initial planting density. The UK climate is warmer, the UK growing season is longer and UK soils are generally richer. Willow SRC should grow more rapidly in the UK than in Sweden. Final yield potential, ('carrying capacity') of UK willow SRC may not be higher than equivalent plantings in Sweden however, as growth will be restricted by the onset of the first limiting resource, (Begon *et al.*, 1998, p256–264). At these high planting densities light and space could be the limiting resources, both of which are dictated by planting spacing rather than climatic conditions etc. Hence, to convert the 15,000 cuttings/ha Swedish result to UK conditions only the early portion of the logistic curve, where the benefits of improved climate and soil nutrient status can be fully realised before space and light become binding, is modified .

Armstrong (*forthcoming*) quotes a mean annual increment of 12.7 dry tonnes/hectare/year over a 3 year growth stage for the top-yielding UK willow clone planted at 10,000 cuttings/ha. The equivalent figure for the best Swedish clone at the same planting density is 9.4 dry tonnes/hectare/year. Scaling the 3 year yields between Sweden and the UK in this ratio modifies the exponential parameter to 1.01. Hence, the form of logistic yield curve proposed for willow SRC grown in the UK at the ARBRE initial planting density of 15,000 cutting/ha is (Figure A2.1);

$$g(t) = \frac{66}{\left(1 + e^{(1.99 - 1.01 \cdot t)}\right)} \tag{A2.4}$$