ELSEVIER

Ecological Economics 25 (1998) 291–301

ECOLOGICAL
ECONOMICS

ANALYSIS

Industrial hemp's double dividend: a study for the USA

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Received 12 August 1996; accepted 10 March 1997

Abstract

The impacts on domestic industries and the quality of the environment of permitting industrial hemp production in the United States are explored. These impacts are modelled in three States of the World, that reflect alternative assumptions about technology. A linear programming model of domestic textile fibre, oil seed, pulp logs, pulp and paper industries is employed. The objective of the model is total land use minimisation. The impact on domestic industries of permitting industrial hemp production are substantial in each State of the World. Economic efficiency is measured in terms of total direct land use required to produce a desired level of physical output. There appears to be a double dividend associated with allowing industrial hemp production in each State of the World: land use decreases and environmental quality improves. This can be interpreted as a decrease in the ecological footprint of production. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: Industrial hemp; Double dividend; Land minimisation; Ecological footprint; Linear programming

1. Introduction

The production of industrial hemp (*Cannabis sitiva L.*) may soon be widely permissible in the US; a number of states are currently considering allowing its production. However, the US Drug Enforcement Administration currently will not issue licences for the commercial production of industrial hemp (Friedman, 1995). Industrial hemp cannot be used for medicinal or recreational purposes, as it contains little of the active agent delta-9-tetrahydrocannabinol (THC). What will be the economic and environmental impacts in the US of a wide-scale introduction of industrial hemp?

Valuable economic and environmental qualities of industrial hemp are acclaimed by industrial

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PII S0921-8009(97)00040-2

hemp's supporters (e.g. Conrad, 1994; Roulac, 1995). Industrial hemp is claimed to be high yielding with low input demands, requiring no biocides and little fertiliser in comparison with cotton, for which it is an excellent substitute. Industrial hemp products are also substitutes for products derived from fossil fuels, such as synthetic fibres (textile and rope), plastics and fuel, and wood-based products, such as paper and particle board.[1] The claimed environmental benefits of industrial hemp would certainly be welcomed by those concerned with the quality of the US environment. Is there a double dividend to be gained from growing industrial hemp, in terms of reduced costs accompanied by environmental benefits?

In the spirit of an ecological economic approach to environment-economy interactions, efficiency is judged rather differently from the approach used in neoclassical economics. Here we judge the efficiency of the economic system to meet desired physical outputs in terms of total land use minimisation (where land use is considered the cost to society), rather than employing the neoclassical approach of economic cost minimisation to achieve a given level of output. The physical representation of costs, employed in this paper circumvents the problems of the relative arbitrariness of current prices, which have been affected by government subsidies, tariffs, externalities, public goods, etc. It also avoids the need to adjust these imperfect market prices by using relatively ad hoc procedures to calculate the 'shadow' prices employed in a neoclassical approach.

The two aims of this paper are to explore under three States of the World:

1. the impacts on domestic textile fibre, oil seed, pulp logs, pulp and paper industries of permitting industrial hemp production in the US;
2. the extent to which a double dividend results from permitting industrial hemp production in the US, as measured by the impacts on land use and also on five environmental damage indicators.

This second aim can also be interpreted as an analysis of the extent to which the ecological 'footprint' of producing a desired level of output with a specific technology is smaller for the US when industrial hemp is permissible, compared to the US in the current situation in which industrial hemp production is prohibited. Here we use the definition of the ecological footprint of a technology as that land area required on a continuous basis to produce a flow of output and assimilate the accompanying waste, regardless of where that land may be located (see Rees and Wackernagel (1994) and Wackernagel and Rees (1995) for excellent discussion and application of the ecological footprint concept). It should be noted that only a partial ecological footprint analysis is undertaken here in which only the direct land use resulting from production is included (see Section 3.2).

This paper can be seen as an application of the teleological approach to envisioned futures of Proops et al. (1996). There it is argued that the achievement of sustainable economic activity will require the exploration of possible future States of the World that are both sustainable and achievable, which might be taken as goals or 'tele'. As it is often suggested that industrial hemp production could be an environmentally friendly substitute for cotton and extensive forestry, and as it is certainly a crop which could be grown in many parts of the world, we consider it worthy of consideration as a potential element of a future 'sustainable world'.

Section 2 outlines the model developed for this study. The results are presented and discussed in Section 3. Conclusions are drawn and areas for further research are outlined in Section 4.

2. Model

The model employed in this study is not a comprehensive description of the US economy today, or in the future. However, it captures sufficient detail of those aspects of the current and a potential future US economy to allow a quantitative analysis of the major impacts on the domestic economy of permitting industrial hemp production in three 'States of the World'. In particular, a number of important substitution

[1] See Roulac (1995) p. 25, for the array of products that can be produced from hemp.

possibilities among inputs and outputs in the textile fibre, oil seed, pulp logs, pulp and paper industries are present in the model.

Section 2.1 outlines the technology that is captured in the model, while the solution procedure and the output constraints on the model are discussed in Section 2.2. The six scenarios in which the model is employed are detailed in Section 2.3.

2.1. Technology

The model of the US industries used in this study is described by eleven production processes (described in detail in Appendix A).[2] The data used refer to 1992, unless otherwise stated. Process 1 employs land and fertiliser to produce hemp fibre, hurds and oil seed. The hemp fibre, from the bark of the hemp stem, is suitable for textiles or can be pulped for use in paper production. Hemp hurds, the woody core of the hemp stem, are suitable for paper production after pulping. Hemp oil seed can be used in human and animal food production, as well as in the production of paints, fuel and soap (Conrad, 1994; van Dam, 1995; Walker, 1994; Wirtshafter, 1995).

Process 2 requires land, fertiliser and biocides and other agrochemicals, to produce cotton textile fibre and cotton oil seed. Cotton and hemp textile fibres are considered here to be perfect substitutes for each other, and collectively referred to here as textile fibre. Hemp and cotton oil seeds are also considered perfect substitutes for each other, and in aggregate are referred to here as oil seeds. Textile fibre and oil seed are end products in this model.

Process 3 utilises land to produce pulp logs. The scenarios employed in this study (see Section 2.2 for details) use the variants in which this process is either low or high yielding. The coefficient for the low yield is derived from an average US timber yield that includes both lumber and pulp logs. The high yield coefficient is derived from pine plantation data. As no data for the 1992 yield of US pulp logs alone could be obtained from the literature, the 1992 pulp logs yield is assumed to lie within the range captured by the low and high yield.

Processes 4 through 10 are pulping processes. Thermo-mechanical and sulfate processes are modelled separately for each of the raw material inputs: hemp fibre; hemp hurds and pulp logs. A thermo-mechanical process is also modelled for a pulping process that uses recycled paper as an input. Thermo-mechanical processes use predominantly heat and mechanical methods to separate pulp fibres. By contrast, the sulfate process relies on chemical processes to achieve fibre separation. Each process requires steam and energy to produce pulp, which is considered to be the same regardless of the process used. Also produced are carbon dioxide and waste. In the production of a unit of pulp, thermo-mechanical processes use relatively little of the above raw material inputs compared with the sulfate processes, and are also less steam intensive than the sulfate processes, but are more energy intensive than the sulfate processes. Unlike the thermo-mechanical processes, the sulfate processes also require natural gas as an input, and also produce energy as an output. The energy output from the sulfate process is produced from the combustion of residues, which results in a net energy output from the process. Waste matter is considered to be non-recyclable and sent to landfill sites.

It should also be noted that while only the sulfate and thermo-mechanical pulping processes are modelled, these were used in the production of approximately 89% (79 and 10%, respectively) of the total US virgin wood pulp in 1992 (United Nations, 1994).

Process 11 uses pulp, other materials (mostly clays), steam and energy to produce paper and carbon dioxide.

The model specifically does not include the synthetic textile fibre component of the textile fibre industry, due to the large share of US consumption (56% of total US textile consumption in 1992, as compared with 32% for cotton consumption) and the vastly different production techniques employed, as compared with cotton and hemp fibre production (derived from Meyer and Skinner, 1995).

[2] Excess capacity is assumed to exist in all processes (with land quality not a constraint), and capital is assumed to be process specific.

A brief summary of the eleven processes can be given in the usual activity analysis notation used for linear models; this is given in Table 1. As is usual, the symbol '⊕' represents 'combined with' and the symbol '→' represents 'is produced'. The actual coefficients for the inputs and outputs are omitted, but are given in Appendix A.

2.2. Solving the model and output constraints

The model is set up to be solved as a linear programming model.[3] The objective in the optimisation procedure is land use minimisation. This objective is consistent with the ecological footprint approach to technology assessment. The model is constrained: by the technology described in the previous Section; in the paper process to use the proportion of recycled pulp to total pulp that was employed in the 1992 paper industry (30%); to produce at least the 1992 US output of paper (derived from United States Department of Commerce, 1994 Ch. 10); to produce textile fibre and oil seed quantities of at least the 1992 US output of cotton textile fibre and cotton oil seed output.

Table 1
The processes used in the model, in activity analysis form

Principal product	Production
1. Hemp	Land ⊕ Fertiliser → Hemp Fibre ⊕ Hurds ⊕ Hemp Oil Seed
2. Cotton	Land ⊕ Fertiliser ⊕ Biocides → Cotton Fibre ⊕ Cotton Oil Seed
3. Pulp logs	Land → Pulp Logs
4. Thermo-mechanical fibre pulp	Hemp Pulp Fibre ⊕ Steam ⊕ Energy → Fibre Pulp ⊕ CO_2 ⊕ Waste
5. Sulfate fibre pulp	Hemp Pulp Fibre ⊕ Steam ⊕ Energy ⊕ Natural Gas → Fibre Pulp ⊕ Energy ⊕ CO_2 ⊕ Waste
6. Thermo-mechanical hurd pulp	Hurds ⊕ Steam ⊕ Energy → Hurd Pulp ⊕ CO_2 ⊕ Waste
7. Sulfate hurd pulp	Hurds ⊕ Steam ⊕ Energy ⊕ Natural Gas → Hurd Pulp ⊕ Energy ⊕ CO_2 ⊕ Waste
8. Thermo-mechanical wood pulp	Pulp Logs ⊕ Steam ⊕ Energy → Wood Pulp ⊕ CO_2 ⊕ Waste
9. Sulfate wood pulp	Pulp Logs ⊕ Steam ⊕ Energy ⊕ Natural Gas → Wood Pulp ⊕ Energy ⊕ CO_2 ⊕ Waste
10. Thermo-mechanical recycled pulp	Recycled Paper ⊕ Steam ⊕ Energy → Recycled Pulp ⊕ CO_2 ⊕ Waste
11. Paper	Pulp ⊕ Other Materials ⊕ Steam ⊕ Energy → Paper ⊕ CO_2

2.3. Scenarios

Six scenarios are considered in this paper. Industrial hemp production is prohibited (reflecting the current situation in the US) or permissible (as in a potential future situation of the US) under each of three States of the World; these are:

1. State of the World 1: low pulp logs yield, and the 1992 proportion of total sulfate pulp to total virgin pulp;
2. State of the World 2: high pulp logs yield, and the 1992 proportion of total sulfate pulp to total virgin pulp;
3. State of the World 3: high pulp logs yield, with no restriction of the proportion of total sulfate pulp to total virgin pulp.

State of the World 1 probably most closely reflects the 1992 situation in the US. In State of the World 2, all pulp logs are produced in high yielding plantations. States of the World 1 and 2, in which the low and high pulp logs yields are employed, respectively, can be considered as representing the limits within which the 1992 situation in the US was located.

State of the World 3 employs the high pulp logs yield and lifts the requirement for total sulfate pulp to be the 1992 proportion of total virgin pulp. Removing the latter constraint in State of the World 3 allows pulp production to switch from the relatively land-inefficient sulfate process, to the relatively land-efficient thermo-mechanical process. Such a switch would also mean that the relatively low pulp yield, but low energy intensive, sulfate process, would be substituted by the relatively high pulp yield, but high energy intensive, thermo-mechanical process.

[3] The model is solved using Microsoft Excel Version 5 'Solver', and is available as a Microsoft Excel Version 5 file on 3.5 inch disk from Dave Alden.

Table 2
Results from land use minimisation in six scenarios

Scenario:	Today 1	Hemp 1	Today 2	Hemp 2	Today 3	Hemp 3
Sulfate pulp = 0.79*Virgin pulp:	Yes	Yes	Yes	Yes	No	No
High or low pulp logs yield:	Low	Low	High	High	High	High
Objective						
Total land use (million ha)	204.85	21.44	14.43	13.97	9.68	8.83
Land						
Hemp land (million ha)	0.00	21.44	0.00	7.54	0.00	7.54
Cotton land (million ha)	4.51	0.00	4.51	0.00	4.51	0.00
Pulp logs land (million ha)	200.35	0.00	9.92	6.44	5.17	1.29
Textile fibre						
Hemp textile fibre (million t)	0.00	3.53	0.00	3.53	0.00	3.53
Cotton textile fibre (million t)	3.53	0.00	3.53	0.00	3.53	0.00
Oil seed						
Hemp oil seed (million t)	0.00	16.08	0.00	5.65	0.00	5.65
Cotton oil seed (million t)	5.65	0.00	5.65	0.00	5.65	0.00
Pulp						
Hemp TM[a] fibre pulp (million t)	0.00	0.00	0.00	7.65	0.00	7.65
Hemp sulfate fibre pulp (million t)	0.00	9.93	0.00	0.00	0.00	0.00
Hemp TM hurd pulp (million t)	0.00	10.05	0.00	2.40	0.00	28.26
Hemp sulfate hurd pulp (million t)	0.00	27.90	0.00	10.25	0.00	0.00
TM wood pulp (million t)	10.05	0.00	10.05	0.00	47.88	11.97
Sulfate wood pulp (million t)	37.83	0.00	37.83	27.57	0.00	0.00
Output constraints						
Paper (million t)	76.00	76.00	76.00	76.00	76.00	76.00
Total textile fibre (million t)	3.53	3.53	3.53	3.53	3.53	3.53
Total oil seed (million t)	5.65	16.08	5.65	5.65	5.65	5.65
Environmental damage indicators						
Total net energy use (GWh)	69.93	38.70	69.93	47.21	193.62	123.80
Total CO_2 emissions (million t)	128.60	89.47	128.60	107.90	166.94	117.47
Total waste production (million t)	6.01	5.68	6.01	5.86	6.54	6.26
Total biocides and other agrochemicals use (million t)	0.02	0.00	0.02	0.00	0.02	0.00
Total fertiliser (million t)	0.58	7.61	0.58	2.68	0.58	2.68

[a]TM = thermo-mechanical.

3. Results and discussion

The results from the optimisation procedure to minimise land use in each of the six scenarios are presented in Table 2. The three scenarios in which industrial hemp is prohibited are referred to as 'Today', and the three scenarios in which industrial hemp is permissible are referred to as 'Hemp'. The State of the World which exists is referenced by the number that follows 'Today' or 'Hemp' and corresponds to those used for the State of the World in the previous section.

The results presented in Table 2 will be discussed in relation to the two foci of this study: the impact on US industries of permitting industrial hemp production; the extent of industrial hemp‘s environmental double dividend.

3.1. Impact on US industries of permitting industrial hemp production

3.1.1. State of the World 1

As the reader will recall, in State of the World 1 the 1992 proportion of total sulfate pulp to total virgin pulp constraint applies, and there is a low pulp logs yield.

Permitting industrial hemp production in State of the World 1 results in a complete switch away from the growing of cotton and pulp logs only (Today 1) to industrial hemp production only (Hemp 1). The output constraints for paper and textile fibre are all met and exceeded for oil seeds as a consequence of industrial hemp fibre, hurds and hemp oil seed production. Even if desirable, such a restructuring of the economy would clearly take time to achieve.

When considering the practical implications of large scale production of industrial hemp as a substitute for pulp logs in pulp and paper production, it should be noted that industrial hemp is a seasonal and bulky crop. To address the seasonality issue, storage facilities would be required, either on farms or at pulp mills. To constrain transportation costs that typically result when moving bulky commodities, small scale pulping plants could be established close to areas in which industrial hemp is produced.

It is also interesting to note that in meeting the output constraint for paper, produced from hemp fibre and hurds, the oil seed constraint is exceeded by a factor of about two in Hemp 1. The reason for this is that hemp fibre, hurds and oil seed are assumed to be jointly produced in fixed proportions.

Hemp land use in Hemp 1 is only about 10% of the combined land use for cotton and pulp logs production in Today 1. Such a saving of land, mostly forest land, would be welcomed by many.

3.1.2. State of the World 2

The reader will recall that in State of the World 2, the 1992 proportion of total sulfate pulp to total virgin pulp constraint applies, and there is a high pulp logs yield.

In this State of the World, permitting industrial hemp production results in a complete switch away from cotton growing (Today 2) to the growing of industrial hemp (Hemp 2). This effect was also observed in State of the World 1. However, unlike Hemp 1, pulp logs continue to be grown in Hemp 2. The reason for this is that producing pulp for paper production from high yield pulp logs is more land efficient than producing pulp from hemp fibre or hemp hurds. Pulp from hemp fibre and hemp hurds is, however, also produced. This is because hemp fibre, hurds and oil seed are jointly produced. In meeting the oil seed constraint, hemp fibre in excess of that required to meet the textile fibre constraint, and hemp hurds, are available for pulping.

It is also interesting to note that the area of the pulp logs land use in Today 1 is approximately twenty times that in Today 2. This is because the high pulp log yield in State of the World 2 is about twenty times that of the low pulp log yield in State of the World 1.

3.1.3. State of the World 3

State of the World 3, as the reader will recall, is a world in which there is no constraint on the proportion of total sulfate pulp to total virgin pulp, and there is a high pulp logs yield.

Permitting industrial hemp production in State of the World 3 results again in a complete switch away from cotton, and a partial switch away from pulp logs production (Today 3) to industrial hemp and pulp logs production (Hemp 3). Given that there is no requirement for a specific proportion of virgin pulp to be produced via the sulfate process in State of the World 3, the land use minimisation objective results in the production of only thermo-mechanical pulp. This is because the thermo-mechanical pulp process requires less hemp fibre, hemp hurds or logs, and is therefore more land-efficient than the sulfate pulp process.

Hemp land use in Hemp 3 is the same as in Hemp 2. The reason for this is that even though it is more land-efficient to produce pulp from pulp logs than either hemp fibre or hemp hurds, the oil seed output constraint requires the resultant hemp land use. It is also interesting to note that land for growing pulp logs in Hemp 3 is only 17% of the hemp land use in Hemp 3, and 20% of the pulp logs land in Hemp 2.

3.2. Industrial hemp's double dividend

The double dividend for industrial hemp is explored through consideration of the impact on total land use and also five environmental damage indicators in each of the Today and Hemp scenarios.

The environmental damage indicators reported in Table 2 have each been the subject of concern in both the US and other countries for a variety of reasons. Energy use is often used alone as an environmental quality indicator, as most energy is derived from fossil fuels, the production and consumption of which often results in pollution. Carbon dioxide emissions are the major cause of the enhanced greenhouse effect, which has attracted much attention worldwide, and the control of which is addressed by the Framework Convention on Climate Change. Waste production is reported because the disposal of solid waste, mostly in land-fill sites, has attracted attention due to the seepage of residues from these sites, and the relative social importance of the remaining possible sites. Concern over the use of biocides and other agrochemicals in crop production has existed for some time, as has concern over excessive use of synthetic fertilisers.

Each of the five environmental damage indicators reported in Table 2 is considered to be inversely related to environmental quality. That is to say, environmental quality improves as an environmental damage indicator decreases. We do not propose a weighting system for aggregating changes in the environmental damage indicators to determine the overall impact on environmental quality. A complete ecological footprint analysis would translate the environmental damage indicators into the equivalent land area required to produce fertiliser, biocides and other agrochemicals, and assimilate solid waste and carbon dioxide emissions. The optimisation procedure for solving the model would then be required to account for these indirect land uses, as well as the direct land use already incorporated. This is beyond the scope of this paper. Here, for each environmental damage indicator, comparisons need to be made across the two scenarios (Today and Hemp) within each State of the World.

In each of the three States of the World, total land use in the Hemp scenario is less than in the Today scenario, and all the environmental damage indicators, except for fertiliser use, are lower in the Hemp scenario than in the Today scenario. The reason fertiliser use is greater in the Hemp scenarios than the Today scenarios is that in the former, industrial hemp production, which requires fertiliser, partially or fully substitutes for pulp logs production, which does not require fertiliser. If the negative impact on environmental quality from increased fertiliser for industrial hemp is considered to be out-weighed by the environmental benefits associated with decreases in energy use, carbon dioxide emissions, waste production and biocide use, a double dividend for industrial hemp production exists. That is, land use is reduced and environmental damage is reduced. This result can be interpreted in terms of the impact on the ecological footprint of producing the desired quantities of textile fibre, oil seed and paper. Permitting the production of industrial hemp reduces the ecological footprint, except that part representing fertiliser use.

For scenarios Hemp 1, 2 and 3, there does appear to be an inverse relationship between total land use and the environmental damage indicators. As total land use increases, the environmental damage indicators decrease, except for fertiliser use. We can thus say that scenarios Hemp 1, 2 and 3 exhibit a positive relationship between environmental costs and environmental benefits, except in the case of fertiliser use.

Of these three Hemp scenarios, Hemp 1 requires more than twice the total land use than used in Hemp 2 and 3, and Hemp 2 requires more total land than Hemp 3. Hemp 1 produces the lowest, or equal lowest, levels of each of the environmental damage indicators, except fertiliser use, which is almost three times greater than the next highest. The reason why fertiliser use is so great in Hemp 1, as compared with Hemp 2 and 3, is that only industrial hemp is grown in Hemp 1, unlike Hemp 2 and 3 in which pulp logs are also produced, which do not require fertiliser as an input. Hemp 2 produces lower, or equally low, levels of each of the environmental indicators than Hemp 3.

The greatest reduction in total land use resulting from permitting industrial hemp production occurs in State of the World 1. This is largely due to the inefficient use of land in the production of pulp logs in Today 1, compared with industrial hemp production in Hemp 1. The lowest total land use is achieved in State of the World 3. This is because pulp is produced only from the thermo-mechanical process, which is more land-efficient than the sulfate process. As the thermo-mechanical process is also more energy intensive, directly and indirectly (for it requires more steam) than the sulfate process, the environmental damage indicators for energy use and carbon dioxide emissions are larger for Hemp 3 than Hemp 1 and 2. A similar argument can be used to explain why Hemp 3 results in more waste production than Hemp 1 and 2.

4. Conclusions and further research

The relatively simple linear programming model employed in this study has allowed a quantitative analysis of the impacts of permitting industrial hemp production on the US textile fibre, oil seed, pulp logs, pulp and paper industries in three States of the World. The model also allowed the exploration of the extent of a double dividend from permitting industrial hemp production, for the same three States of the World.

The impacts on the identified domestic US industries could be fairly substantial, depending upon the State of the World. The results indicate that industrial hemp production would totally replace cotton textile and cotton oil seed production in each State of the World considered. Industrial hemp production would also partially or completely replace pulp logs production, depending upon the State of the World considered.

The results tend to indicate that permitting industrial hemp production produces a double dividend in each of the three States of the World considered. The partial ecological footprint analysis undertaken here, that accounts for only the direct land use in production, showed a smaller footprint when industrial hemp production is permitted. It is also clear that the full ecological footprint associated with producing the desired quantities of textile fibre, oil seed and paper is also reduced when industrial hemp production is permitted. It remains for further research to analyze whether allowing industrial hemp production will also reduce economic costs, implying a triple dividend. It also remains for further research to explore the investment, employment and social adjustment implications of these results. We would speculate that once the community has made the decision to permit industrial hemp production, these adjustments would be relatively small. However, it is acknowledged that due to the power of those that have vested interests in not allowing industrial hemp production, making this decision is not easy.

The model could also be used in further research to explore a variety of other scenarios in which alternative constraints are employed. For example, if the proportion of recycled pulp to total pulp in the paper process is increased, it has been found to allow cotton production in each of Hemp 1, 2 and 3. The reason for this result is that oil seed production is more land-efficient in cotton production than in industrial hemp production. The sensitivity of this result to the model's technology coefficients could also be explored.

The technology in the model could be altered to investigate the impact on the results presented here of alternative production processes, such as organic cotton production rather than the biocide dependent process described here.

Further research opportunities exist to consider the transition toward the comparative static worlds modelled here, in which industrial hemp production is permissible. The use of a neo-Austrian capital approach would be appropriate for such work (Faber and Proops, 1993).

Acknowledgements

We would like to thank Keele University for allowing Dave Alden to visit the Environmental Policy Unit as a Research Fellow, and The University of Melbourne for funding this period of Dave Alden's study leave, during which this research was undertaken. We would also like to thank the following individuals who assisted our research efforts: Colin Baker; Jim Bolton; Andrew Dickinson; Todd Goninon; Andy Goodwin; Ian Low; Peter Messenger; Dorothy Myers; Sue Riddlestone; Burkhard von Schotheim and Caroline

Sullivan. The constructive comments of the referees: Anthony Guglielmi, William Rees and a third anonymous referee, added to the quality of this paper, for which we are grateful.

Appendix A

In the description of the eleven production processes of the model presented below, the coefficients are expressed in: hectares (ha) for land; megajoules (MJ) for steam; kilowatt hours (kWh) for energy; and metric tonnes (t) for all other quantities. For a specific process, the coefficients are scaled per unit of one of the outputs. The addition symbol within a circle, ⊕, means 'combined with' and the arrow, →, implies that the inputs are 'transformed' into the outputs. Thus, for a specific production process each complementary input and each joint output is a unique proportion of all inputs and outputs in that process.

Process 1: Hemp
0.4 Land[a] ⊕ 0.142 Fertiliser[b] → 1 Hemp Fibre ⊕ 3 Hurds[a] ⊕ 0.3 Hemp Oil Seed[a]

Process 2: Cotton
1.2769754 Land[c] ⊕ 0.165 Fertiliser[d] ⊕ 0.0056 Biocides and Other Agrochemicals[d] → 1 Cotton Fibre ⊕ 1.6006797 Cotton Oil Seed[c]

Process 3: Pulp Logs
High Yield: 0.05 Land[e] → 1 Pulp Logs
Low Yield: 1.01 Land[f] → 1 Pulp Logs

Process 4: Thermo-mechanical (TM) Fibre Pulp
2 Hemp Pulp Fibre[g] ⊕ 1168 Steam[h] ⊕ 834 Energy[i] → 1 TM Fibre Pulp ⊕ 0.0739 CO_2 (Steam)[h] ⊕ 0.51708 CO_2 (Energy)[j] ⊕ 0.0963 Waste[k]

Process 5: Sulfate Fibre Pulp
4.324 Hemp Pulp Fibre[k] ⊕ 2621 Steam[h] ⊕ 166 Energy[h] ⊕ 0.007145 Natural Gas[h] → 1 Sulfate Fibre Pulp ⊕ 967 Energy[k] ⊕ 0.1657 CO_2 (Steam)[h] ⊕ 0.1027 CO_2 (Energy)[j] ⊕ 0.01822 CO_2 (Natural Gas)[h] ⊕ 0.083 Waste[k]

Process 6: Thermo-mechanical (TM) Hurd Pulp
2 Hurds[l] ⊕ 1168 Steam[h] ⊕ 834 Energy[h] → 1 TM Hurd Pulp ⊕ 0.0739 CO_2 (Steam)[h] ⊕ 0.51708 CO_2 (Energy)[j] ⊕ 0.0963 Waste[k]

Process 7: Sulfate Hurd Pulp
4.324 Hurds[k] ⊕ 2621 Steam[h] ⊕ 166 Energy[h] ⊕ 0.007145 Natural Gas[h] → 1 Sulfate Hurd Pulp ⊕ 967 Energy[k] ⊕ 0.1657 CO_2 (Steam)[h] ⊕ 0.1027 CO_2 (Energy)[j] ⊕ 0.01822 CO_2 (Natural Gas)[h] ⊕ 0.083 Waste[k]

Process 8: Thermo-mechanical (TM) Wood Pulp[m]
2.16 Pulp Logs ⊕ 3892 Steam ⊕ 2778 Energy → 1 TM Wood Pulp ⊕ 0.24613 CO_2 (Steam)[n] ⊕ 1.72236 CO_2 (Energy) ⊕ 0.104 Waste

Process 9: Sulfate Wood Pulp[m]
4.67 Pulp Logs ⊕ 8730 Steam ⊕ 552 Energy ⊕ 0.0238 Natural Gas → 1 Sulfate Wood Pulp ⊕ 1044 Energy ⊕ 0.55209 CO_2 (Steam)[n] ⊕ 0.34224 CO_2 (Energy) ⊕ 0.06069 CO_2 (Natural Gas) ⊕ 0.09 Waste

Process 10: Thermo-mechanical (TM) Recycled Pulp[m]
1.12 Recycled Paper ⊕ 1120 Steam ⊕ 472 Energy → 1 Recycled Pulp ⊕ 0.07083 CO_2 (Steam)[n] ⊕ 0.29264 CO_2 (Energy) ⊕ 0.076 Waste

Process 11: Paper[m]
0.9 Pulp [o] ⊕ 0.1 Other Materials ⊕ 7003 Steam ⊕ 670 Energy → 1 Paper ⊕ 0.44287 CO_2 (Steam)[n] ⊕ 0.4154 CO_2 (Energy)

The following equations are derived from the above processes to produce aggregates that are either used as inputs in the above processes or define variables reported in Table 2.

Total Hemp Fibre = Hemp Textile Fibre + Hemp Pulp Fibre

Total Textile Fibre = Hemp Textile Fibre + Cotton Fibre

Total Oil Seed = Hemp Oil Seed + Cotton Oil Seed

Total Virgin Pulp = TM Hurd Pulp + Sulfate Hurd Pulp + TM Fibre Pulp + Sulfate Fibre Pulp + TM Wood Pulp + Sulfate Wood Pulp

Total Pulp = Total Virgin Pulp + Recycled Pulp

Total Net Energy Use = TM Fibre Pulp Energy + Sulfate Fibre Pulp Energy + TM Hurd Pulp Energy + Sulfate Hurd Pulp Energy + M Wood Pulp Energy + Sulfate Wood Pulp Energy + Recycled Pulp Energy + Paper Energy − Energy from Sulfate Fibre Pulp − Energy from Sulfate Hurd Pulp − Energy from Sulfate Wood Pulp

Total CO_2 Emissions = TM Fibre Pulp CO_2 (Energy) + Sulfate Fibre Pulp CO_2 (Energy) + TM Hurd Pulp CO_2 (Energy) + Sulfate Hurd Pulp CO_2 (Energy) + TM Wood Pulp CO2 (Energy) + Sulfate Wood Pulp CO_2 (Energy) + Recycled Pulp CO_2 (Energy) + Paper CO_2 (Energy) + TM Fibre Pulp CO_2 (Steam) + Sulfate Fibre Pulp CO_2 (Steam) + TM Hurd Pulp CO_2 (Steam) + Sulfate Hurd Pulp CO_2 (Steam) + TM Wood Pulp CO_2 (Steam) + Sulfate Wood Pulp CO_2 (Steam) + Recycled Pulp CO_2 (Steam) + Paper CO_2 (Steam) + Sulfate Fibre Pulp CO_2 (Natural Gas) + Sulfate Hurd Pulp CO_2 (Natural Gas) + Sulfate Wood Pulp CO_2 (Natural Gas)

Total Waste Production = TM Fibre Pulp CO_2 (Waste) + Sulfate Fibre Pulp CO_2 (Waste) + TM Hurd Pulp CO_2 (Waste) + Sulfate Hurd Pulp CO_2 (Waste) + TM Wood Pulp CO2 (Waste) + Sulfate Wood Pulp CO_2 (Waste) + Recycled Pulp CO_2 (Waste)

Total Fertiliser Use = Hemp Fertiliser + Cotton Fertiliser

Total Biocides and Other Agrochemicals Use = Cotton Biocides and Other Agrochemicals

Total Land Use = Hemp land + Cotton Land + Pulp Logs Land

Source of coefficients

[a] Derived from van Dam (1995, p. 407), industrial hemp is assumed to produce a fibre yield of 2.5 t/ha, 7.5 t/ha of hurds and 0.75 t/ha of hemp oil seed.

[b] Mean of the optimum doses of mineral fertilisers (nitrogen, phosphate and potash) suggested by Kozlowski et al. (1995, p. 63).

[c] Derived from Food and Agriculture Organisation of the United Nations (1994).

[d] Derived from Economic Research Service and National Agricultural Statistics Service (1993). For fertiliser: aggregation across mineral fertilisers (nitrogen, phosphate and potash), weighted by proportion of total surveyed land to which each fertiliser is applied. For biocides and other agrochemicals: aggregation across biocides and other agrochemicals for surveyed land.

[e] Derived from a yield of 20 t/ha per year over a 20 year rotation assumed for a *Pinus radiata* plantation (Dickinson, 1996).

[f] Derived from Lewis et al. (1996, p. 40) for projected volume of annual removals of US timber in the year 2000, by assuming the average weight of timber is equal to that of poplar (*populus*) given in Krotov (1994, p. 147).

[g] Messenger (1996).

[h] Assumed to be the same as the respective coefficient in the respective wood pulp process, weighted by the ratio of energy in the TM fibre pulp process to energy in the TM wood pulp process.

[i] Baker (1996).

[j] Energy use multiplied by the average CO_2 per unit of electricity produced in the US, derived from 1992 total emissions of CO_2 from electric utilities (United States Department of Energy, 1994 p. 102) and the 1992 total electric utility net generation of electricity (United States Department of Energy, 1993 p. 217).

[k] Assumed to be the same as the respective coefficient in the respective wood pulp process, weighted by the ratio of fibre in the TM fibre pulp process to logs in the TM wood pulp process.

[l] Assumed to be the same as for fibre in the TM fibre pulp process.

[m] Virtanen and Nilsson (1993, appendices A and B).

[n] This results from the production of steam, which is assumed to be produced by the combustion of natural gas. This equates to 0.00006324 t of CO_2 per MJ of steam (from Virtanen and Nilsson, 1993, pp. 138, 142).

[o] To be consistent with the 1992 US paper industry usage of recycled pulp, 30% of this pulp is constrained to come from process 10; the TM recycled pulp process.

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