Market Dynamics of Allocating Land to Biofuel and Forest Sinks

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Abstract: Large scale use of biofuel, that is fuel derived from biological materials, especially in combination with reforestation of big areas, can lead to low cost reduction of atmospheric carbon dioxide level. In this paper a model of three markets – fuel, wood products and land – is considered with the aim to evaluate the impact of large scale biofuel production and forestry on the markets and to estimate the cost of a policy aimed at the reduction of the carbon content in the atmosphere. It is shown that the cost is lower than has been expected previously.

Keywords: Kyoto Protocol; Biofuel; Carbon sequestration

1. INTRODUCTION

It has been suggested [Read, 1994] that large scale biofuel production, especially in combination with sequestration forestry, can achieve low cost reduction in greenhouse gas levels, in particular CO_2, and hence lead to meeting the ultimate objective of the Framework Convention on Climate Change (FCCC) – to "stabilise greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system".

Biofuel (fuel derived from biological materials) displaces fossil fuels and thus, through fossil fuels not extracted, prevents release of underground fossil carbon. Biofuel is the only renewable fuel providing chemically stored energy of the kind to which the current energy supply system has become adapted and can potentially substitute for fossil fuel with minimal infrastructural change, providing a backstop technology until other innovative technologies can take a sufficient market role.

Forestry offer a large mitigation potential with modest costs, low risk and other benefits and is one of the few 'no regrets' opportunities available in most countries all over the world [Kohlmaier et al., 1997]. The Kyoto Protocol's Article 3.3 recognises enhancing forest sinks as a mean of meeting the proposed emissions reduction commitments entered into for 2008–2012 by Annex 1 Parties to the FCCC. This places forestry alongside biofuel production as a land using activity that can – within the jurisdictions of these Parties, and possibly elsewhere through cooperation with other Parties – be encouraged to achieve the ultimate objective of the FCCC. Such a policy assumes a large-scale intervention in the allocation of land as well as in the energy market. This leads to the question what will be the costs and consequences of such a policy. It is believed that the first attempt to model the interacting market impacts of policy-specified land use changes that are focused on carbon mitigation, including biofuel production and sequestration forestry together, was the FLAMES model (Fuel/Forest/Food Land Allocation Model for Energy/Environment Sustainability) [Read, 1997]. FLAMES is a partial equilibrium model of three interacting markets – energy, forest products and land – under action of large scale land allocation for biofuel production and sequestration forestry. In this paper we report further development and refinement of the model.

The main objective of this paper is to model the impact of large-scale biofuel production on the world fuel and conventional wood products markets and to estimate the cost of a policy aimed at the reduction of the carbon content in the atmosphere by means of sequestration forestry and biofuel production. We study the response of three interacting markets – energy, forest products and land – to user-specified allocations of large areas of land for biofuel production and carbon sequestration (the extraction of atmospheric carbon and storing it in growing trees). We abstract from the detail of markets for fuel and power and for forest products (with "energy" standing for all fuels and other commercial energy resources and "wood" standing for pulp, roundwood chips and other conventional forest products).

2. MODEL

The model comprises three market equations for three price variables: the consumers' price of fuel, P, the price of conventional forestry product, s, and the rent on land, r. The model assumes short term financing, with the net costs of the land allocation policy transferred, on the "polluter pays" principle, directly to energy consumers by the means of a dedicated tax on fossil carbon emitted. The dedicated carbon-tax is equivalent to the absorption obligation proposed by Read [1994]. The prime source of the carbon emission is fossil fuels, and hence it is the subject of the carbon-dedicated tax. Biofuel is not a subject to the tax since its use does not increase the atmospheric carbon content. That is the consumers' price of both biofuel and fossil fuel, along with the producers' price of biofuel, is P. If a dedicated tax per tonne of fossil carbon emitted is τ, then the consumers' price P is related to the producers' price of fossil fuel p via the equation

$$P=p+\tau. \qquad (1)$$

2.1 Land Market

Following Read [1999], we assume that all the available land L is partitioned into five classes: land for conventional use (agriculture, husbandry, etc.) L_c; existing plantation land (commercial forests, i.e. commercial plantations plus natural forest likely to be taken for timber production) L_p; land allocated for biofuel production (or "the short-rotation policy land") L_{short}; land for sequestration (or "the long-rotation policy land") L_{long}; and land left to wilderness L_{wild}. That is, $L=L_c+L_p+L_{short}+L_{long}+L_{wild}$. The area of the available land, L, represents all the land that is either currently in land-based productive use or might be so used. It excludes from the available land area permanently barren land – desert, ice and urban coverage – and most natural forests that are unlikely to be exploited for logging. We assume that the available land L is either constant or slowly decreasing (due to increase of the area of urban coverage) with time [Read, 1999], $L(t)=k_1-k_2t$. The land for conventional use, L_c, is a function of time t and rent r, monotonically increasing with the economic growth over time, and decreasing with rent. Following Read [1999], we assume that

$$L_c(t,r)=(k_{15}-k_{16}r)(1-\alpha\tau)^{k_{17}}\exp(k_Lt)\frac{N(t)}{N_0}.$$

Rent r increases as the area of the land left to wilderness shrinks, i.e. $\partial L_{wild}/\partial r<0$. As in [Read, 1999], we assume that $L_{wild}=(k_{13}/\mathrm{r})^{k_{14}}$, $L_p=k_{18}-k_{19}t$. Here k_i and α are positive parameters, τ is the carbon-dedicated tax, $N(t)$ is the global population at time t and N_0 is the population at beginning of the policy. An allocation of land for carbon sequestration and biofuel production is policy specified, i.e. L_{short} and L_{long} are given functions of time. A way to define such land allocations is to specify a planting policy, i.e. to define planting programs for long- and short-rotation land.

2.2 Biofuel and Wood Production

The lands L_p, L_{long} and L_{short} produce biomass M_p, M_{long} and M_{short}, respectively. The lands L_p and L_{long} are allocated to trees, while the biofuel land L_{short} is used for shorter-rotation plants. If $l_{long}(t)$ and $l_{short}(t)$ are planting programs for long- and short-rotation lands L_{long} and L_{short}, t_{long} and t_{short} are the rotation periods and d_{long} and d_{short} are the land productivity, then the biomass harvested annually from these lands is proportional to the areas planted t_{long} or t_{short} years ago, that is $M_{long}(t)=d_{long}l_{long}(t-t_{long})$ and $M_{short}(t)=d_{short}l_{short}(t-t_{short})$. We assume that a constant portion (say $1/t_p$, where t_p is the rotation period) of the existing plantations L_p is harvested annually. Then the biomass M_p obtained is assumed to be proportional to the harvested area and to the land productivity d_p, $M_p=d_pL_p/t_p$. From Read [1999], we assume that the productivity of forestry, d_p and d_{long}, are constant whereas due to technological development the productivity of the biofuel land grows with time, $d_{short}=d_0(1+2t/t^*)$, where t^* is the time horizon (here $t^*=70$ years). Harvested biomass can be used to produce conventional wood product (timber), of mass W, and bioenergy B. Note that we measure biomass and wood product in units of mass (tonne), while biofuel is measured by its energy content: one tonne of dry biomass contains k_M units of energy ($k_M\approx 20$ GJ/tonne). Note $B_j/k_M+W_j\leq M_j$, where j is p, $long$ or $short$. Let $\kappa_j=B_j/k_MM_j$, $\sigma_j=W_j/M_j$, that is κ_j and σ_j are fractions of biofuel B_j and timber W_j in the biomass M_j harvested from the land L_j. The fraction of each product depends on the products' prices. Following

Read [1999], and presuming that the same technological process is applied to trees from lands L_p and L_{long}, we assume that $\kappa_{short}=k_{35}+(k_{35}-1)\chi$, $\kappa_p=\kappa_{long}=k_{36}+(k_{36}-1)\chi$ and $\sigma_{short}=(1-k_{35})(1+\chi)$, $\sigma_p=\sigma_{long}=(1-k_{36})(1+\chi)$, where $\chi=2/\pi\ \arctan(A(s\text{-}k_M P)/(s_0\text{-}k_M P_0)\text{-}B)$. Here, A=24 B =12 and P_0, s_0 are initial values of P and s respectively. Initially $\chi\approx 1$ and, with k_{35}=0.95 and k_{36}=0.635, the product split for M_{short} is 90:10 and for mature timber 25:75. (Note that P is the price of energy while s is the price of biomass; therefore the coefficient k_M appears in the equations.)

2.3 Fuel and Timber Demand-supply Balance

For a market in equilibrium supply equals demand. For the energy market, supply is a sum of non-biofuel energy, H, and biofuel, B that is $H+B = D$. Here, the demand for energy D is a monotonically decreasing function of consumers' price; the supply P of non-biofuel energy H is an increasing function of producers' price p. The supply of the biofuel, B, is composed of the biofuel from the short-rotation land, the biofuel from the long-rotation land and the commercial forests, that is $B=B_{long}+B_{short}+B_p$, where $B_{long}=\kappa_p k_M M_{long}$, $B_p=\kappa_p k_M M_p$ and B_{short} = $\kappa_{short} k_M M_{short}$. As in Read [1999] we assume that demand shifts with time and is depressed by the macro-economic impact of the dedicated tax, and has underlying constant elasticity structure,

$$D(P,t)=\left(\frac{k_{10}}{P}\right)^{k_{11}}(1-\alpha\tau)^{k_{12}}\exp(k_B t)\frac{N(t)}{N_0} \tag{2}$$

$$H(p,t)=(k_6+k_7 p)\exp(k_8 t), \tag{3}$$

where k_6, k_7, k_8, k_9, k_{10}, k_{11}, k_{12}, k_B, and α are positive parameters. Fossil fuel energy, H_F, which is primarily responsible for carbon dioxide emission and is a subject of the carbon-dedicated taxes, makes a fraction of the non-biofuel energy H. Following [Read, 1999], $H_F(p,t)=(k_6+k_7 p)\exp(k_{21}t)$, where $0< k_{21} < k_8$, to represent decarbonisation of non-biofuel energy due to technological progress. For the timber market the wood product supply W is a sum of the long-rotation land wood product, $W_{long}=\sigma_p M_{long}$, the commercial forestry product, $W_p=\sigma_p M_p$, , and the short-rotation land wood product, $W_{short}=\sigma_{short} M_{short}$. In equilibrium supply meets demand, that is $W_p+W_{long}+W_{short}=D_W$. The demand for timber D_W decreases with the product price s and grows with time t. From Read [1999],

$$D_W(s,t)=\left(\frac{k_{31}}{s}\right)^{k_{32}}(1-\alpha\tau)^{k_{33}}\exp(k_W t)\frac{N(t)}{N_0}, \tag{4}$$

where k_{31}, k_{32}, k_{33}, k_W, are positive parameters.

2.4 Policy Cost

In equilibrium the total revenue meets the cost of policy. The total revenue is composed of the revenue from the biofuel sales, $U_B=P(B_{long}+B_{short})$, the revenue from the wood product sales, $U_W=s(W_{long}+W_{short})$ and the revenue from the tax on the carbon emitted,

$$T=\tau H_F\,. \tag{5}$$

The revenue from the biofuel and the timber from the commercial plantations L_p are not included since these accrue to existing commercial operators. The policy costs, Q, is a sum of the total rent, $R=r(L_{long}+L_{short})$, the establishment costs proportional to the areas sown, $\hat{q}_{short}l_{short}(t)+\hat{q}_{long}l_{long}(t)$, annual costs of maintenance proportional to the land areas, $q_{short}L_{short}+q_{long}L_{long}$, and the costs of harvesting assumed to be proportional to biomass harvested from the corresponding area, $\tilde{q}_{short}M_{short}+\tilde{q}_{long}M_{long}$. Hence, in equilibrium $P(B_{long}+B_{short})+s(W_{long}+W_{short})+\tau H_F=Q$, where $Q=r(L_{long}+L_{short})+\hat{q}_{short}l_{short}+\hat{q}_{long}l_{long}+q_{short}L_{short}+q_{long}L_{long}+\tilde{q}_{short}M_{short}+\tilde{q}_{long}M_{long}$ and $q_{short}, q_{long}, \hat{q}_{short}, \hat{q}_{long}, \tilde{q}_{short}, \tilde{q}_{long}$ and q_{long} are positive constants. The costs-revenue balance for the commercially used lands L_p is $R_p+{}+Q_p+\hat{Q}_p+\tilde{Q}_p=PB_p+sW_p$, which is not included in the model.

3. THE DYNAMIC MODEL

To introduce dynamics into the model we assume, [Morishima, 1960], that the product prices rise in response to excess demand in a market. We have a system of three markets in interaction: the energy market, the timber market and the land market. Thus we obtain the equations

$$a_p\frac{dP}{dt}=D-H-B \tag{6}$$

$$a_s\frac{ds}{dt}=D_W-W \tag{7}$$

$$a_r\frac{dr}{dt}=L_p+l_{short}+L_{long}+L_{wild}+L_c-L \tag{8}$$

for the energy markets, the timber markets, and the land markets, respectively. Here a_p, a_s, a_b are positive constants which are proportional to the corresponding time-scale and inversely proportional to the speeds of response. Analogously we assume that the carbon taxes tax τ rises if "demand" – the policy cost – exceeds "supply"– the revenue from biofuel and timber sales and the tax revenue,

$$a_\tau \frac{d\tau}{dt} = Q - P(B_{long} + B_{short}) - s(W_{long} + W_{short}) - \tau H_F \tag{9}$$

Here a_τ is a positive constant which is proportional to the corresponding time-scale and inversely proportional to the speeds of response. The system (6), (7), (8), (9) should be solved simultaneously with the equation of the atmospheric carbon balance. The total atmospheric carbon content, C, increases with burning of the fuel supplied, and decreases due to absorption of the carbon by ocean and terrestrial ecosystem, the short-rotation land, the long-rotation land, and the old plantations. We assume that emission of the carbon due to use of biofuel from the short-rotation land equals absorption of the atmospheric carbon for the biofuel growth. Then

$$\frac{dC}{dt} = \beta_H H_F + \beta_B(B_{long} + B_p) + \beta_W W_{short} - \beta_p(L_p + L_{long}) - O_{ocean} \tag{10}$$

where β_H, β_B and β_W are the carbon content of the fossil fuel, the biofuel and the wood product respectively; $\beta_p = \beta_{long}$ are the rate of the atmospheric carbon absorption by long-rotation and old plantation land; O_{ocean} is the rate of the atmospheric carbon absorption by the ocean. We assume [Read, 1999] that $O_{ocean} = \beta_0(C - C_{cr})$, where β_0 is the rate of carbon diffusion into ocean and C_{cr}=560.

4. SIMULATION

Following Read [1997 and 1999] let us consider market responses under three scenarios: (a) no policy; (b) allocation of land for biofuel production only; (c) allocation of land for biofuel production and for sequestrational forestry. Under the third scenario sequestration is not treated as permanent, as in previous studies [Marland, 1998], but as a several decades low cost "buffer stock" of carbon, to be utilised as wood and biofuel at a time when demand for this raw material has developed. This keep open the precautionary option of 100 per cent use of this stock as biofuel in the event science reveals a low threshold for adverse climate surprise. The land allocation for these three scenarios are given by Figure 1.

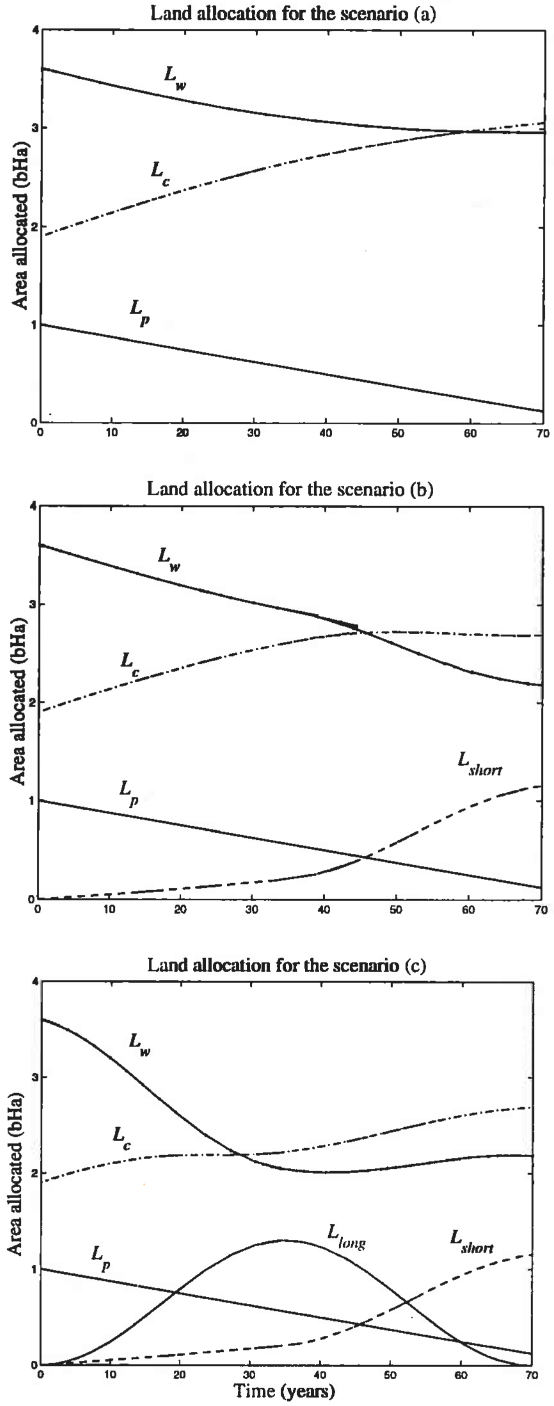

Figure 1. Land allocation for the three scenarios: (a) no policy land; (b) allocation of land for biofuel and (c) allocation of land for biofuel and sequestration forestry.

We will assume that the policy is applied for 70 years. Although in principle variable, a time horizon of 70 years has been used in all the work to date. This period broadly represents both twice the rotation period for forestry and twice the turnover period for long-lived energy sector capital stock.

The former is convenient for modelling but the latter is more significant consideration because energy sector technological inertia related to heavy sunk costs provides the main obstacle to a rapidly effective response strategy that stabilises or reduces current greenhouse gas levels through change in the energy sector alone. The 70-years time horizon is preferred to the 100-years time horizon used by some analysts [e.g. Manne and Richels, 1992] because a longer horizon, with three generations of capital re-equipment, enables technological change in developed countries to be put off in a way that fails to provide the lead that is looked for by developing countries. Also, it exceeds the apparent time scale of some Holocene climate transitions, for which the evidence is controversial but not trivial–[Ankin et al., 1993], the triggers unknown, and a repetition of which would be catastrophic, given current and prospective population levels. The global population $N(t)$ is approximated by a fifth order polynomial

$$N(t)=\sum_{j=1}^{6} c_j t^{6-j}\,, \qquad (11)$$

where c_1=4.1067×10^{-4}, c_2=-0.211864, c_3=36.631, c_4=-2.272×10^3, c_5=9.5760×10^4, and c_4=5.4219×10^4 which fits with good accuracy the World Bank Official Population Dynamics Forecast [United Nations, 1995] on the time interval from 1950 to 2100. Figure 2 represents the corresponding market responses for the three scenarios.

The change of atmospheric carbon contents for the scenario is given by Figure 3. As demonstrated by Figure 3, allocating large areas of land to two activities – a long-term buffer stock of carbon sequestrated from the atmosphere and short-rotation biofuel production – has a very substantial beneficial impact on the timing and quantum of greenhouse gas level reductions. With both biofuel production and buffer stock sequestration a comparatively low carbon-dedicated tax is required for up to 35 years to meet the cost of creating the buffer stock. After 35 years the dedicated tax is zero and – given the assumption of rising biomass production productivity – the policy actually brings a profit. After 35 years, energy prices are also reduced on account of additional biofuel supply from the desequestration process. The results indicate that an integrated forestry-based strategy, in which land in first used for buffer stock sequestration and subsequently converted to biofuel production may offer the prospect of controlling greenhouse gases levels more effectively and at lower cost than has previously been shown to be practical [Read, 1997].

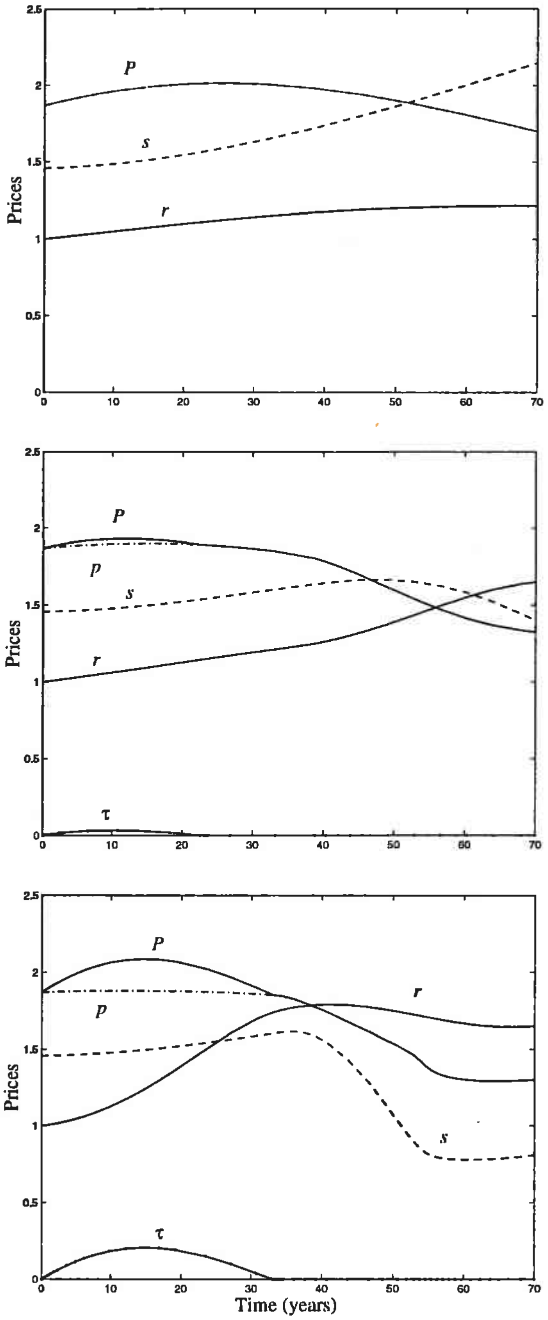

Figure 2. The consumers' and producers' prices of energy and tax ($/GJ), rent (10×$/Ha) and price of wood products (100×$/t) for the three scenarios respectively.

5. DISCUSSION AND CONCLUSION

An objective of this work was to substantiate the intuition advanced in [Read, 1994] since corroborated by others [Kohlmaier et al., 1997] that land allocation policy with the aim of biofuel production and sequestration forestry can play a major role in controlling greenhouse gas levels. Another objective was to investigate the market impacts of such land allocation policies with a view to quantifying these effects, identifying potential winners and losers and illuminating policy options that can lead markets outcomes towards the least cost achievement of a safe level of greenhouse gases in the atmosphere. In relation to the first objective, it is apparent as a fairly secure conclusion that, if sufficient land is used, the impact on greenhouse gas level, in particular CO_2, of policy driven land allocations is such as has not been regarded as practicable under alternative policies, [Schneider and Goulder, 1997].

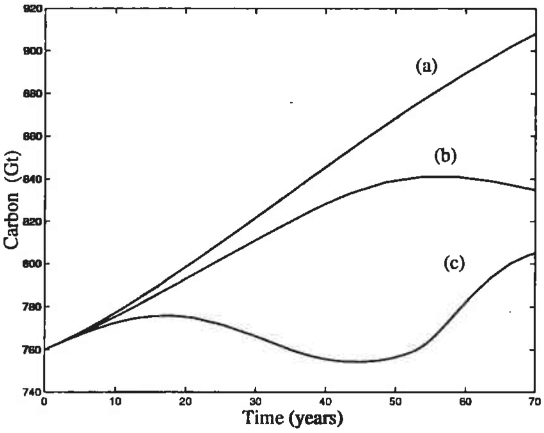

Figure 3. Atmospheric carbon contents for the three scenarios.

The model demonstrated, on a global basis, that large-scale allocations of land to the growing of trees, either on long rotation for traditional forest products or on short rotation for biofuel, can achieve low cost reductions in greenhouse gas levels that are otherwise infeasible. Despite the obvious policy relevance of these results, they are not sufficient to be applied to policy issues since the model is global while policy is determined at national levels. An avenue for further research is development of a multi-regional model with inter-regional trade flows able to establish world prices for fossil fuel, biofuel and woody raw materials. The world prices would enable individual countries model to be developed, establishing whether the country will export or import these products.

Given the geo-political aspects of policy, a model which treats the globe as a whole can provide little insight. This aspect is reinforced by the reality that FCCC Annex 1 countries are mainly located in higher latitudes with temperate climate and moderate to poor growing conditions. Together with oil producing countries, they also have greater sunk costs in the energy sector and lower growth prospects than developing economies. Thus a regionalized model that at least reflects these broad differences is needed before the market impacts can be modelled satisfactorily. Such a model, distinguishing a low energy cost, low photosynthetic productivity, high income and reducing growth region from a contrasting developing region, is a current research priority.

6. REFERENCES

Ankin, M *et al.*, Climate Instability during the last interglacial period recorded in the GRIP ice core, *Nature*, *364*, 203–207, 1993.

Kohlmaier, G.H., M. Weber and R.A. Houghton, Carbon Dioxide Mitigation in Forestry and Wood Industry, Springer-Verlag, Berlin 1997.

Manne, A.S., and R.G. Richels, *Buying Greenhouse Insurance: the Economic Costs of Carbon Dioxide Emission Limits*, MIT Press, Cambridge, MA, 1992.

Marland, G., The prospect of solving the CO_2 problem through global reforestation. DOE/NBB-0082, National Technical Information Service, Springfield, VA 1988.

Morishima, M., A reconsideration of the Walras-Cassel-Leontief model of general equilibrium, *Mathematical Methods in the Social Sciences*, 1959 Proceedings of the First Stanford Symposium, Edited by K.J. Arrow *et al* Stanford 1960.

Read, P., *Responding to Global Warming: the Technology, Economics and Politics of Sustainable Energy*, ZED Books, London 1994.

Read, P., Food, fuel, fibre and faces to feed: Simulation studies of land use change for sustainable development in the 21st century, *Ecological Economics*, *23* 81–93, 1997.

Read, P., The role of biomass in meeting greenhouse gas reduction targets: land allocation modeling of key market impacts, Massey University, Palmerston North, 1999.

Schneider, S.H., and L.H. Goulder, Achieving low-cost emissions targets, *Nature*, *389*, 13–14, 1997.

United Nations, World Population 1950-2050 (Medium Variant), Population Studies from UN, World Population Prospects, 1994 Revision, UN 1995.