SECTION 10

Effectiveness of carbon accounting methodologies for LULUCF and harvested wood products in supporting climate-conscious policy measures.

Effectiveness of carbon accounting Methodologies for LULUCF and harvested wood products in supporting climate-conscious policy measures

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SUMMARY

The Kyoto protocol is an important example of an accounting methodology that aims to meet the United Nations Framework Convention on Climate Change (UNFCCC) objective to reduce concentrations of greenhouse gases in the atmosphere. In addition to facilitating the reporting of emissions of greenhouse gases resulting from consumption of fossil fuels, the Protocol permits countries to take into account vegetation based sinks and changes in these through Land Use, Land Use Change and Forestry, and potentially carbon dynamics in harvested wood products (HWP). As part of elaboration of the Kyoto Protocol methodology, a number of LULUCF carbon accounting methods, with special reference to forestry systems and HWP, have been developed and articulated. Any such methodology needs to reconcile and address a number of scientific and political aspirations, ultimately supporting the objective of the UNFCCC. This paper presents an analysis and evaluation of different accounting methodologies for the forestry sector, with particular focus on their likely impact at national and international level. Although an evaluation of accounting methodologies in support of the Kyoto Protocol is an important focus of this study, an important aim is to present a general method of analysis that could be used to evaluate any proposed accounting system in support of the objective of the UNFCCC. The analysis is based on a hypothetical world consisting of eight model countries that vary in land area, percentage forest cover and consumption of fossil fuels. To simplify initial analysis it was assumed that the countries would carry on current practice (i.e. business as usual or BAU) over the period from 1990 up to 2150. The relative impact of alternative methodologies on the potential carbon credits or debits accrued by the eight model countries is assessed and compared with a reference case estimate of the emission increase or reduction.

Compared to fossil fuel emissions, construction of baselines for LULUCF and HWP is complicated, requiring a lot of assumptions about past, present and future LULUCF and HWP trade/utilisation. It is questionable, however, whether very sophisticated assumptions would yield more reliable BAU projections than simple assumptions. Even if BAU assumptions about LULUCF are kept very simple, resultant projections can be highly non-linear, with very large fluctuations and discontinuities in the predicted carbon net sink/source. Adoption of alternative methods of accounting for HWP can result in differences in percentage changes reported that are as high as ±15%, although the different HWP accounting methods have only marginal influence on the relative ranking of the different countries in terms of reported percentage change in carbon net sink/source, particularly if estimates are accumulated over longer periods. Reported estimates of carbon net sink/source are highly sensitive to choice of baseline and in particular choice of LULUCF accounting index. The picture is extremely confusing when combined with a short (5 year) commitment and reporting interval. When viewed over long time intervals, reported estimates of carbon net sink/source under BAU may not be very sensitive to choice of baseline, while adoption of fairly simple LULUCF accounting indices may result in a ranking of countries in terms of emissions changes that is similar to that obtained using complicated annual sink/source estimates. It is essential to test the sensitivity of the above conclusions to consideration of non-BAU scenarios and increased complexity in representation of model countries. Although the above analysis is based heavily on the provisions of the Kyoto Protocol, the approach to the analysis is valid in general and many of findings would apply to any accounting system that may be adopted by countries in support of the ultimate objective of the UNFCCC.

INTRODUCTION

The ultimate objective of the United Nations Framework Convention on Climate Change (UNFCCC, 1992) is to stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. The Kyoto protocol (UNFCCC, 1998) aims to support the UNFCCC objective by committing participating countries to reductions in national anthropogenic greenhouse gas emissions, the most important being carbon dioxide (CO_2), arising mainly from the use of fossil fuels. Apart from accounting directly for changes in consumption of fossil fuels, the Protocol also specifically allows countries to take into account vegetation based sinks and sources of greenhouse gases, and changes in these arising from Land Use, Land Use Change and Forestry (LULUCF). These activities have not been clearly defined, and the sink and source accounting rules have not been comprehensively specified or agreed. Methods for estimating fossil fuel emissions are relatively easy to define and agree, but the estimation of LULUCF emissions is very complicated, particularly if carbon dynamics in harvested wood products (HWP) is to be included.

As part of elaboration of the Kyoto Protocol methodology, a number of LULUCF carbon accounting methods, with special reference to forestry systems and HWP, have been developed and articulated in the scientific literature (Kirschbaum *et al.*, 2001; Fearnside *et al.*, 2000; Fruit and Marland, 2000; IPCC Special Report, 2000; Maclaren, 2000; Jackson, M. 1999; Moura-Costa and Wilson, 1999; Chomitz, 1998; Tipper and de Jong, 1998; Winjum *et al.*, 1998). Variants of these methodologies that are very different from each other may be specified, depending on the definition of system boundaries, so-called ‘baselines’ and the treatment of ‘additionality’ as specified in the Kyoto Protocol, notably in Articles 2, 3.3 and 3.4.

Any methodology accounting for sinks and sources of carbon arising from LULUCF activities and HWP dynamics needs to reconcile and address a number of scientific and political aspirations. Apart from a basic need for physical and logical consistency, the accounting system needs to directly support the ultimate policy goal of stabilising atmospheric greenhouse gas emissions, as well as ensuring equitable treatment of participating nations that have very different levels of vegetation cover and fossil fuel consumption. In addition, potential for conflict with international conventions on protection of forests and biodiversity must be avoided. There may also be a need to provide a system that can deliver consistent results and statistics at project level and national level.

This paper presents an analysis and evaluation of different accounting methodologies for the forestry sector, with particular focus on their likely impact at national and international level. Particular objectives of this study were to evaluate:

- The impact of the different LULUCF and HWP accounting methods on the reduction estimates reported by participating countries.
- The effectiveness of different LULUCF and HWP accounting methods in achieving the UNFCCC objective.
- The robustness of alternative interpretations or realisations of the provisions of the Kyoto Protocol.

Although an evaluation of accounting methodologies in support of the Kyoto Protocol is an important focus of this study, an important aim is to present a general method of analysis that could be used to evaluate any proposed accounting system in support of the objective of the UNFCCC.

METHODS

Definition of model system of countries

A hypothetical world consisting of eight model countries (named Circle, Diamond, Oblong, Oval, Pentagon, Star, Trapezium and Triangle) was defined. The model countries were designed to contrast with one another in terms of carbon emissions arising from national energy consumption, land area, areas of land covered by old-growth and commercially productive forests, and annual net change in forest area as specified for the base year of 1990 (Table 1). The model countries were also designed to be comparable in broad terms with real-world countries listed in Annex I of the Kyoto Protocol, or ‘non-Annex I’ countries that might seek to participate in an endeavour such as Kyoto Protocol in the future. The principal characteristics of each country can be summarised qualitatively as shown in Table 1.

Business as usual (BAU) scenario

To simplify initial analysis it was assumed that the countries would carry on current practice (i.e. business as usual) over the period from 1990 up to 2150.

Specification of BAU carbon emissions from fossil fuel consumption

For the business as usual scenario, annual emissions of carbon as carbon dioxide from fossil fuel consumption were assumed to remain at the same level for each country over the period from 1990 to 2150, as shown in Table 1, thus

$$e_{i,t} = e_{i,1990}$$

where $e_{i,t}$ is the CO_2 emission (in units of tonnes carbon) from fossil fuel consumption in the ith country in year t.

Initial conditions and BAU projection for LULUCF

For each country, land cover in the year 1990 was classified as being either old-growth forest, commercially productive forest or non-forest land. In order to simulate carbon emissions arising from changes in land cover over the period of interest under business as usual, model projections were made of carbon dynamics in land-based vegetation for a period significantly preceding 1990 up to 2150. This was necessary because, for example, the carbon sink/source due to vegetation in 1990 is likely depend to some extent on land cover changes that took place prior to 1990. Accordingly projections of land cover were made from a set of initial conditions for each country that were specified for the year zero. This initial year was selected arbitrarily as being long enough before the year 1990 to represent long term changes in land cover and resultant carbon dynamics.

All 'old-growth' forests existing in the year 1990 were represented as having been created in year zero. Commercially productive forests existing in the year 1990 were represented as having been created by conversion from either non-forest old-growth forests uniformly over a period between 1890 and 1990. Constant rates of conversion were assumed, and values were selected that would add up to the overall rate of deforestation or afforestation as shown for each country in Table 1. For years succeeding 1990, afforestation or deforestation was assumed to continue at the 1990 rate. All afforestation was assumed to take place through creation of commercially productive forests on non-forest land, while all deforestation was assumed to take place through loss of old-growth forests to non-forest. Afforestation or deforestation was assumed to continue indefinitely over the period 1990 to 2150, subject to the following constraints:

1. The total forest area in any country was constrained to not fall below 50% of the total forest area for the year 1990.
2. The forest area in any country was constrained to not expand over more than 10% of the land area not currently under forest.
3. Loss of old-growth forest (through either deforestation or conversion to commercial forest) was constrained such that the area of old-growth forest should not fall below 2% of the land area of the country. Any deforestation was assumed to continue at the 1990 rate through loss of commercially productive forest areas subject to constraint 1.

The resultant pattern of changes in percentage land cover assumed for each country over the period 1990 to 2150 is summarised in Figure 1a-h. Having defined these land cover transformations it was possible to calculate annual estimates of land area undergoing conversion between the three land cover types.

Carbon dynamics in vegetation

The Forest Research CARBINE model was used to simulate changes in carbon stocks in forests in each country, and annual estimates of carbon sinks and sources due to land cover changes were derived from the stock changes. The model also calculated changes in carbon stocks in harvested wood products (HWP) from stands in each country.

CARBINE was developed originally as a model for simulating carbon accumulation in individual forest stands and in any associated HWP (Thompson and Matthews, 1989) and was at this stage of development similar in structure to other stand-level models of carbon dynamics in forests and HWP that have been developed (Harmon et al., 1990; Dewar, 1990, 1991; Dewar and Cannell, 1992; Apps and Kurz, 1993; Kurz *et al.*, 1993; Heath and Birdsey, 1993; Nabuurs and Mohren, 1993, 1995; Fischlin and Bugmann, 1994). CARBINE was later adapted to use detailed forest estate inventory data as input and a primitive sub-model representing soil carbon dynamics was added. This version of the model was used to estimate carbon stocks, sinks and sources in British forests. In a later version of CARBINE, treatment of carbon sequestration in HWP was simplified but sub-models were included to estimate the impact on fossil fuel consumption of changes in the supply of different categories of HWP including bioenergy, particleboards, paper and sawnwood. This model, now similar in specification to the GORCAM model (Marland and Schlamadinger, 1995; Schlamadinger and Marland, 1998), was applied at the stand level and also to the British forest estate to evaluate the impact on carbon sinks and sources of alternative forest management and wood utilisation options (Matthews, 1994, 1996).

For this study, further modifications to the model were necessary in order to represent progressive annual transitions between land cover classes, specifically:

- Gradual afforestation, reforestation or deforestation.
- Gradual conversion of old-growth forest to commercially productive forest.
- Gradual conversion of commercially productive forest to old-growth forest.
- Combinations of the above transitions.

Forest inventory data supplied to CARBINE usually consists of a set of initial conditions for a base year in which a national forest estate is defined in terms of forest areas broken down according to soil type, tree species, productivity class and prescribed management. Further input data then specify projected transitions between forest types and changes in stand management. By comparison, the land cover data provided for the model countries considered here was very abbreviated as follows:

- Non-forest land was assumed to have zero carbon stocks.
- Changes in carbon stocks in soil were ignored.
- The same models were applied in all countries to represent conversion of harvested wood to products, displacement of fossil energy through substitution, and retention of carbon in HWP and landfill.
- Forest stands in all countries were represented using two growth models, each with one productivity class.

In effect, carbon dynamics in forest stands and non-forest areas was represented using using just two alternative models of stand growth. The first of these models was based on yield tables for Sitka spruce stands of average productivity growing in Britain (Edwards and Christie, 1981), and was used to represent old-growth forests. The management prescription for this model was for no harvesting other than at time of clear fell, thus if no clear felling was carried out the accumulation of carbon stocks was very high. Conversion of old-growth stands to non-forest land (deforestation) was represented by complete removal of the carbon stock predicted by the model to have accumulated in the stand, with stem biomass and a fraction of branch biomass assumed to be utilised in HWP or to provide bioenergy. Non-forest land was therefore assumed to have zero carbon stocks. Commercially productive stands were represented using a model based on yield tables for Corsican pine stands of relatively high productivity growing in Britain (Edwards and Christie, 1981). The management prescription for this model included regular silvicultural thinning prior to final harvest of the stand at theoretical economic rotation age.

Harvested stem biomass and a fraction of branch biomass were assumed to be utilised in HWP or to provide bioenergy. CARBINE is similar to other models in its approach to simulating the retention of carbon in HWP. For each species of tree simulated, harvested wood is first allocated to the following wood product categories:

- Waste, bark, fuel
- Paper
- Board products
- Short-lived sawnwood
- Long-lived sawnwood.

Waste, bark and fuel are all assumed to release their carbon over 1 year. Paper is also assumed to be disposed of relatively quickly, although a fraction of disposed paper is assumed to be landfilled, where total loss of carbon is assumed to take up to 40 years. Retention of carbon in board products, short-lived sawnwood and long-lived sawnwood is modelled using nonlinear functions – a high proportion is assumed to be lost within 1 year. The remaining carbon is assumed to be released over approximately 5 years in the case of short-lived sawnwood and between 30-50 years in the case of Board and long-lived sawnwood, depending on species. There has been some concern that in general this approach can lead to anomalous results when using short runs of data (for example 30-50 years). In this study the model was run for the hypothetical countries effectively from ‘pre-history’, and results do not exhibit this artefact. To achieve this many simplifying assumptions are needed, not only about long-term development of forest areas and age class structure in the hypothetical countries, but also about patterns and methods of utilising wood over long periods. The approach of Pingoud *et al.* (2000) was used to calibrate CARBINE using estimates of stocks and fluxes for wood products for the UK derived by inventory methods (Alexander, 1997).

Clear fell was assumed to be followed immediately by establishment of more commercially productive forest stands. Conversion of old-growth forest to commercial forest was represented by complete removal of the old-growth forest carbon stock, as above, followed immediately by simulated establishment of an equivalent area of commercially productive forest. Conversion of commercially productive forest to old-growth forest was represented by continuing to project carbon stocks using the Corsican pine model, allowing silvicultural thinning to continue to take place up to time of clear fell but then retaining carbon stocks indefinitely and permitting them to accumulate. As for old-growth forests, conversion of commercially productive stands to non-forest areas was represented by complete removal of the carbon stock predicted by the model to have accumulated in the stand, with stem biomass and a fraction of branch biomass assumed to be utilised in HWP or to provide bioenergy.

CARBINE generated annual estimates of carbon stocks for each model country from which estimates of the LULUCF carbon net sink/source could be derived by taking first differences. An example of this projection over the period 1990 to 2150 for country Triangle is shown in Figure 2.

Carbon dynamics in HWP and attribution to countries

The wood products survival sub-model of CARBINE produced annual estimates of the carbon net sink/source attributable to HWP harvested in each of the eight model countries. In each year, the carbon net sink/source due to HWP for the hypothetical world was estimated as the sum of these eight estimates:

$$H_t = \sum_{i=1}^{i=8} h_{i,t}$$

where H_t is the carbon net sink/source due to HWP for the hypothetical world (tC y^{-1}) and $h_{i,t}$ is the net sink/source due to wood products in year *t* harvested in the i^{th} country.

Treatment of HWP and allocation of carbon sinks/sources as part of any proposed system of greenhouse gas accounting is currently the subject debate, and four methods have been proposed, known respectively as the IPCC, Production, Stock Change and Atmospheric Flow methods (Winjum *et al*., 1998). Brief descriptions of the four methods with some commentary are provided in Appendix 1, but essentially the IPCC method involves simply ignoring carbon dynamics in HWP, the Production method attributes carbon net/sink sources due to HWP to the producer country, the Stock Change method attributes carbon net/sink sources due to HWP to the consumer country, while the Atmospheric Flow method effectively an unbalanced method, in that it attributes emissions of carbon from destroyed or decayed HWP to the consumer country but does not account for the original in-flow of carbon to the HWP pool of that country.

Calculation of $h_{i,t}$ and H_t was carried out separately for the Production, Stock Change and Atmospheric Flow methods, as defined for each method in Appendix 1. It was trivial for the CARBINE model to represent the IPCC and Production methods of allocating HWP carbon sinks/sources, but representation of the Stock Change and Atmospheric flow methods involved making assumptions about consumption of HWP by different countries. These assumptions were kept as simple as possible. Specifically it was assumed that consumption of wood products (and any associated carbon sink/source) for each country was directly proportional to fossil fuel consumption in that country for the base year of 1990. Thus, having the obtained sum H_t defined above, the net sink/source attributable to each country under the Stock Change and Atmospheric Flow methods was calculated using the following equations:

$$p_{i,t} = \gamma_i H_t$$

$$\gamma_i = \frac{e_{i,1990}}{\sum_{i=1}^{i=8} e_{i,1990}}$$

where $p_{i,t}$ is the HWP carbon net sink/source attributable to the i^{th} country in year t, γ_i is the proportion of H_t attributable to HWP consumption in the i^{th} country.

For the IPCC method, $p_{i,t}$ was set to zero for all countries in all years, while for the Production Method $p_{i,t}$ was set equal to $h_{i,t}$ as defined above. An example of the projected HWP carbon net/sink source over the period 1990 to 2150 for country Triangle, as calculated according to the four alternative methods, is shown in Figure 5.

This modelling approach has also been applied to an evaluation of potential impacts of alternative carbon accounting methodologies for harvested wood products in the UK (Appendix 2). In this case the models used more detailed, country-specific forest and HWP inventory data as inputs or in calibration of functions.

Displacement of fossil fuel consumption by bioenergy and wood products

The supply of bioenergy and solid wood products from forests is assumed to reduce consumption of fossil fuels for energy generation and production of materials. Under BAU, the contribution made by wood to energy consumption is assumed to be already incorporated within the BAU projection of emissions from fossil fuel consumption. Calculations made by CARBINE of the potential impact of wood production on fossil fuel consumption through change are therefore not used in analysis of a BAU scenario, but may be used as a baseline in the analysis of changes from BAU not considered in this study.

LULUCF and HWP accounting indices

In principle the annual carbon net sink/source estimates for each country could be combined directly with equivalent annual estimates of emissions from consumption of fossil fuel. However, currently there is some debate as to whether some form of index based on a transformation or simplification is more appropriate for comparison and combination with emissions estimates from fossil fuel consumption. A number of alternative indices have been proposed by research, policy and commercial groups with three broad and to some extent conflicting objectives:

1. Avoidance of perverse incentives or disincentives (for example disincentives to the legitimate felling of trees or stands as part of sustainable harvesting of forests to provide bioenergy and/or wood products).
2. Avoidance of excessive cost of measuring, monitoring, modelling and/or reporting of carbon sinks and sources attributable to LULUCF.
3. Active provision of incentives favouring commercial forest carbon sequestration projects.

This study evaluated the impact of adopting different accounting indices on the LULUCF carbon net sink/source estimates that would be reported by the eight model countries. A selection of seven example LULUCF accounting indices, representative of the range proposed in the scientific literature or in position statements, was considered, specifically:

- Real-time accounting
- One-off accounting
- Tonne-year accounting
- Advance tonne-year accounting
- Rental accounting
- Benchmark accounting
- Simplified benchmark accounting.

Brief definitions of these indices including details of calculation methods are provided in Appendix 3. In principle these indices can also be used to account for HWP under the Production and Stock Change calculation methods therefore, for consistency, the same index was used for HWP as was selected for LULUCF for these methods. It was also possible to define one-off and benchmark indices for HWP calculated according to the Atmospheric Flow calculation method. On the other hand, indices involving a tonne-year or rental approach cannot be defined for the Atmospheric Flow calculation method, therefore a real-time approach was adopted for HWP as calculated by the Atmospheric Flow method when considering tonne-year and rental LULUCF accounting indices.

Carbon net sink/source

Having computed estimates for each country of carbon emissions from fossil fuel consumption as well as estimates of the LULUCF and HWP carbon net/sink source, the overal carbon net sink/source for each country was calculated according to the following equation:

$$S_{i,t} = e_{i,t} + (l_{i,t} - L_{i,t}) + (p_{i,t} - P_{i,t})$$

where $S_{i,t}$ is the carbon net sink/source for the i^{th} country in year t, $e_{i,t}$ is the emission of carbon due to fossil fuel consumption in the i^{th} country in year t, $l_{i,t}$ is the LULUCF carbon net sink/source (as evaluated by the accounting index selected) and $p_{i,t}$ is the equivalent HWP carbon net sink/source. The terms $L_{i,t}$ and $P_{i,t}$ represent projections of baseline variables for each country that are used to adjust LULUCF and HWP estimates.

LULUCF baseline

Employment of some sort of baseline in the calculation of LULUCF carbon net sinks/sources is implicit in Articles 3.3 and 3.4 of the Kyoto Protocol. The purpose of the baseline is to represent the naturally-occurring and/or BAU component of the LULUCF carbon sink/source – subtracting the baseline estimate from the overall net sink/source as shown in the equation above means that the contribution to $S_{i,t}$ from LULUCF does not include natural phenomena and comprises only sinks and sources that are regarded as human-induced over and above BAU activities. Physical, ethical and political arguments can be deployed to support the case for inclusion of some sort of baseline for LULUCF as shown in equation above, however in practice it is very difficult to agree a method of calculation that is guaranteed to be physically meaningful and equitable to all parties in all cases and there are potential difficulties in calculating baseline projections of LULUCF carbon net sinks/sources based on a hypothetically constructed BAU. There is a case, therefore, for adopting a much simpler approach to baselines, provided this does not distort estimates of $S_{i,t}$ excessively, particularly in the long term. Four alternative approaches to calculation of LULUCF baselines were evaluated in this study as described below.

- Zero. The value of $L_{i,t}$ is set to zero for all countries and for all years. This means that the entire LULUCF carbon net sink/source for each country is counted in the calculation of $S_{i,t}$, with no distinction made as to whether components are naturally occurring, due to BAU, or are the result of actions representing a change from BAU. Strictly, this is not in the spirit of the wording Articles 3.3 and 3.4 of the Kyoto Protocol, but a justification for the adoption of a zero baseline rests, not only on the pragmatic view that it does not require construction of a hypothetical and subjective BAU and projection of the equivalent carbon sinks and sources, but also the atmosphere does not care about the specific origins or causes of sinks and sources of carbon.
- 1990 value. This baseline represents an attempt to keep calculation of the LULUCF carbon net sink/source simple by not having to rely on any sort of hypothetical projection, but without resorting to the extreme option of a zero baseline.
- 1990 projection. For this baseline, projection of $L_{i,t}$ is made for each country by taking the areas of non-forest, old-growth forest and commercially productive forest for the year 1990 and holding these areas constant into the future. These areas are used as input data to CARBINE and the carbon net sink/source for 1990 and future years computed. Changes to forest areas that take place in 1990 are thus ignored. CARBINE projects forward changes in forest age structure that would have occurred had forest areas not changed, and periodic harvesting of stands in commercially productive forests is also accounted for. As a result, CARBINE computes a projection of the LULUCF carbon net sink source that does not account for any deforestation and afforestation taking place in the years 1990 and beyond. Subtraction of this baseline $L_{i,t}$ from $l_{i,t}$ leaves a remainder that represents the carbon net sink/source due LULUCF activities that have taken place since the year 1990 only, as specified in Article 3.3 of the Kyoto Protocol.
- BAU projection. Projection of $L_{i,t}$ is made for each country by constructing a BAU scenario for LULUCF and using CARBINE to compute the resultant carbon net sink/source for the year 1990 and subsequent years. Adoption of this baseline is consistent with the spirit of Article 3.4 of the Kyoto Protocol. The study reported here only considers the BAU scenario for each of the model countries, so for all situations adoption of this baseline means that the LULUCF carbon net sink/source term in the equation above disappears. Although this may be a trivial result in the context of this study, evaluation of this baseline is important when considering how changes from BAU that may occur different countries would be represented in terms of the carbon net sink/source reported.

HWP baseline

Although it can be argued that all carbon sinks and sources due to HWP are clearly human-induced (but not necessarily the result of 'additional' action), in this study it was decided to adopt a baseline for HWP that was the same as that used for LULUCF. This ensured that LULUCF and HWP estimates were treated consistently in the evaluation.

Assigned amount

An important objective of the Kyoto Protocol is to provide a means for participating countries to demonstrate commitment to achieving percentage-based reductions in net emissions of greenhouse gases. Percentage changes in carbon net sinks or sources can be calculated using the following equation:

$$C_{i,t} = 100\frac{(S_{i,t} - R_i)}{R_i}$$

where $C_{i,t}$ is the percentage change in carbon-based emissions reported by the ith country in year t, and R_i is the reference value of the carbon net sink/source used to calculate the percentage for the ith country. In the Kyoto Protocol R_i is known as the ‘assigned amount’ which is to be calculated from estimates of sinks and sources for the year 1990 for each country. Strictly, calculation of a percentage of $S_{i,t}$ should employ a reference value of $S_{i,1990}$. However, Article 3.7 of the Kyoto Protocol stipulates that Ri should be set equal to $e_{i,1990}$ for countries for which $l_{i,1990} \leq 0$ (i.e. the LULUCF carbon net sink/source is not a source) but that Ri should be set equal to $S_{i,1990}$ when $l_{i,1990} > 0$. This study therefore evaluated three alternative methods of calculating $C_{i,t}$, specifically:

- Gross-net approach. The value of R_i was set equal to $e_{i,1990}$ for all countries.
- Net-net approach. The value of R_i was set equal to $S_{i,1990}$ for all countries.
- Article 3.7 approach. For countries with $l_{i,1990} \leq 0$, the value of R_i was set equal to $e_{i,1990}$. For countries with $l_{i,1990} > 0$, the value of R_i was set equal to $S_{i,1990}$.

As a point of detail, if the HWP carbon sink/source is to be included within any accounting system, strictly the value of $l_{i,1990} + p_{i,1990}$ should be used as a test value when adopting an approach such as specified by Article 3.7.

At first sight it may appear that the carbon net sink/source calculated according to the net-net approach represents most faithfully the true percentage annual carbon sink/source to or from the atmosphere attributable to each country in strict physical (mass balance) terms, however in practice problems may arise. For example, if $l_{i,1990} < 0$ (i.e. is a sink) with magnitude comparable to $e_{i,1990}$, then $R_i \rightarrow 0$ and reported percentages will be very large even for small changes in $S_{i,t}$ and often estimates will be unreliable. The reported percentage becomes impossible to calculate in situations where $R_i = 0$, and difficult to interpret in situations where $R_i = 0$. This may be seen as justification for adoption of gross-net accounting either in all cases or specifically for countries where LULUCF is a sink in 1990. On the other hand, by definition gross-net calculation has the potential to misrepresent the magnitude of percentage net emission changes.

Commitment period

Average values of $C_{i,t}$ over periods of years can be calculated, for example the Kyoto Protocol specifies that countries should report average values of $C_{i,t}$ for consecutive five year commitment periods, with the first period covering the years 2008 to 2012. In this study, results were considered as annual projections but also as averages for 5 year periods. Averages for the full simulation period of 1990 to 2150 were also calculated and summarised graphically.

RESULTS AND DISCUSSION

Selection and evaluation of 'default' calculation and projections

Figure 4a-h shows examples of projections of percentage changes in the carbon net sink/source for the eight model countries over the period from 1990 to 2150, calculated as follows:

- Percentage change was calculated according to the approach specified in Article 3.7 of the Kyoto Protocol.
- A baseline of zero was adopted.
- Separate projections were calculated by allocating HWP according to either the Stock Change or Production method. (These are shown respectively as black and grey lines in Figure 4.)
- A real-time accounting index was used.

The projections calculated as above and adopting the Stock Change approach to HWP (black lines in Figure 4) were accepted as a 'default' for each country on the basis that the carbon net sink/source calculated according to this method represented most faithfully the true percentage annual carbon sink/source to or from the atmosphere attributable to each country, while avoiding potential problems arising from adoption of a comprehensively net-net approach. These default projections are a fundamental result of this study and a number of conclusions can be drawn from consideration of their timecourses as illustrated in Figure 6 as outlined below.

Non-linearity of BAU projections

It is evident from the description of methods above that construction of a BAU scenario for LULUCF and HWP is far more complicated than for fossil fuel consumption, and requires many assumptions to be made. In addition, projections of changes in the carbon net sink/source due to LULUCF and HWP exhibit a strongly non-linear and non-intuitive relation to input assumptions. As explained in the methods section and summarised in Figure 1, assumptions made about LULUCF and HWP for each of the eight model countries were kept as simple as possible. For example, rates for afforestation or deforestation were held constant over the period 1990 to 2150, subject to certain minimum and maximum constraints on areas of forest and non-forest land, assumptions about carbon dynamics of different land classes were greatly simplified, and allocation of HWP to consumer countries was based on constant partition coefficients. Despite these simplifications, the benchmark projections of changes in carbon net sink/source shown in Figure 6 exhibit considerable variability and on occasion very large inter-annual fluctuations. This is in sharp contrast to the simplicity of BAU projections for emissions from fossil fuel consumption, for example had Figure 1a-h in fact shown assumptions about future changes in levels of fossil fuel consumption for each country, the resultant projection of changes in carbon emissions to the atmosphere would have exhibited a direct and instantaneous correlation with the assumed levels of consumption.

Unexpected and perverse results

Construction of long-term projections of changes in carbon net sink/source due to LULUCF and HWP may result in a number of unexpected, unintended or perverse results or outcomes as the following examples illustrate.

Projections for country Circle (Figure 4b) and country Oval (Figure 4f) exhibit relatively little change from zero in early years, but after this initial period a discontinuity in the projection occurs such that both countries report very large reductions in the carbon net sink/source. This might give the impression that, after some time, both countries have acted to more than comply with targets set in the Kyoto Protocol. However, from Table 1 and Figures 1b and 1f it is apparent that both countries start in 1990 with relatively high forest area which is deforested progressively in succeeding years. The drastic and rapid reduction in net carbon emissions predicted for these countries merely reflects the fact that these countries have deforested to the up to the practical limit set theoretically in this study. Apparent compliance with emissions in later years therefore arises directly from complete non-compliance and failure to take remedial action up to that point. In reality the halting of deforestation due to practical constraints is likely to take place progressively, and sharp discontinuities in projections such as shown in Figures 4b and 4f will not be observed. In such cases, a deceleration in the rate of deforestation is more probable and as a result the reduction in carbon emissions due to LULUCF will be more gradual than illustrated here, but the ultimate outcome is the same.

Another example of an unexpected and arguably perverse outcome can be observed in the projection country Trapezium (Figure 4h) which, roughly between the years 2105 and 2120 exhibits an episode during which uncharacteristically large reductions in the carbon net sink/source are achieved. From Figure 1h it is apparent that, while this country is not deforesting, nevertheless over the period 1990 to 2105 a progressive conversion of old-growth forest to commercially productive forest is assumed to take place, with resultant reductions in long-term carbon stocks. This only ceases around 2105 because the minimum constraint on the area of old-growth forest for this country is reached at this time. The projected episode of large reductions in carbon emissions is thus a non-linear response to the halting of this conversion process and subsequent carbon dynamics reflect development of the commercially productive forests that have resulted from this transition. A similar episode with the same cause is observed for country Oblong (Figure 4e) right at the beginning of the simulation period from 1990 up to 2005. As a consequence, changes in carbon sinks/sources including LULUCF during the inaugural five-year commitment periods of the Kyoto Protocol reported by country Oblong would show particularly large fluctuations.

Unexpected or unintended results can also arise in cases where countries are actively afforesting under BAU assumptions. For example the projection for country Diamond (Figure 4c) exhibits a progressive reduction in the reported carbon net sink/source over the period 1990 to 2020. This is in response to an ongoing programme of commercial afforestation in country Diamond, however this is assumed to come to a halt around the year 2020 as the theoretical maximum limit for forest area of the country is reached. As a result, the projected carbon net sink/source exhibits a discontinuity at this point, jumping from a predicted large reduction in the carbon net sink/source to a large increase. As with earlier examples, it is unlikely that such sharp discontinuities in projections would be observed in reality but the ultimate outcome such as illustrated for country Diamond may occur progressively for countries that attempt to meet commitments to the Kyoto Protocol in early years through afforestation measures.

Magnitude of trends and fluctuations

For a number of projections in Figure 4 the magnitude of trends and/or fluctuations is very large, notably for countries Circle, Oval (large, long-term change) Diamond, Oblong, Trapezium and to a lesser extent Star (large cycles and interannual fluctuations). For these countries, the contribution of LULUCF and HWP to reported carbon net sinks/sources dominates any influence of fossil fuel consumption under BAU assumptions. Compared to these countries, the influence of LULUCF and HWP on projections for countries Pentagon and Triangle is much less (although still of the order of ±15% for country Pentagon). Countries Pentagon and Triangle have very high emissions from fossil fuel consumption relative to LULUCF and HWP carbon sinks/sources, and as a result the denominator in the equation used in calculating percentage changes is dominated by the contribution from emissions due to fossil fuel consumption. This has the effect of reducing the amplitude of jumps, cycles and fluctuations in projections due to the non-linear response to LULUCF. For the other countries, emissions from fossil fuel consumption do not make such a dominant contribution in the percentage calculation with the result that potentially very large jumps, cycles and fluctuations in projections may be observed, even under BAU assumptions.

Variation of reported results with method of calculation

Assigned amount

The impact of adopting different options for selection of R_i in equation used to calculate percentage changes is illustrated in Table 2 for two example accounting periods of 2008-2012 (Table 2a) and 1990-2150 (Table 2b). Percentage changes in the carbon net sink/source have been calculated for each country according to the default calculation defined above but varying the selection of R_i according to either the gross-net, net-net or strict Article 3.7 approach. As noted in the description of Methods, adoption in general of gross-net accounting could misrepresent countries for which LULUCF was a source in 1990 (see results for countries Star, Oval, Circle, Trapezium and Oblong). The Methods section of the paper also raises the concern that, if net-net accounting is adopted universally, then R_i might in some cases tend to zero or even be negative, greatly distorting the reporting of emissions by countries in such cases. (Specifically this might occur where LULUCF is a big sink relative to fossil fuel emissions in 1990.) In principle this is a real problem that could occur in practice. This situation can only occur if LULUCF is a sink for the country in 1990. In the case of the model countries considered in this study this is only relevant to countries Triangle, Diamond and Pentagon. In fact these countries have very large fossil fuel emissions relative to their LULUCF sinks, and net-net accounting could be acceptable for these countries. On the other hand, a gross-net calculation for these countries overstates the size of the net emission reduction. For country Pentagon, an increase in net emissions compared to 1990 is reported as a decrease when gross-net accounting is used. Calculating percentage increases or reductions using net-net, gross-net and Article 3.7 rules all have potential problems. Although not perfect, adherence to Article 3.7 may avoid the worst of these.

Treatment of HWP

The impact of alternative methods of accounting for HWP is illustrated in Table 3 for two example accounting periods of 2008-2012 (Table 3a) and 1990-2150 (Table 3b). Percentage changes in the carbon net sink/source have been calculated for each country according to the default calculation defined above but allocating sinks and sources due to HWP according to either the IPCC, Production, Stock Change or Atmospheric Flow methods. The observed differences seem to make intuitive sense, for example country Triangle, a very high net consumer of wood products, reports the smallest percentage increase in net sink/source (or even a small percentage decrease) if the Stock Change method is adopted. Production of wood products in country Triangle is so small that percentages reported under the IPCC and Production methods are almost the same. On the other hand, the percentages reported for country Diamond, a very large net producer of wood, exhibit the strongest sink when the Production method is adopted. Percentages reported for country Diamond under the Stock Change and IPCC methods are progressively more conservative. For a five year commitment period (Figure 8a), percentages reported under the Atmospheric Flow method may be drastically different to those reported using the other three methods. If a long accounting period is considered (Figure 8b) percentages reported under the Atmospheric Flow method are significantly different (and more pessimistic) for all but one country. The generally pessimistic results reported under the Atmospheric Flow method are a direct result of the inherent imbalance in the method noted and in Appendix 1, which may also be compounded by double counting with losses of carbon in forests due to harvesting (see Appendix 1). If comparison is restricted to the IPCC, Production and Stock Change methods, differences in percentage changes reported may still be as high as ±15%, although the different HWP accounting methods have only marginal influence on the relative ranking of the different countries in terms of reported percentage change in carbon net sink/source, particularly if estimates are accumulated over longer periods (Table 3b).

Baseline and accounting index

Table 4a-i illustrates the impact of adopting different accounting indices for LULUCF and HWP on the percentage changes in carbon net sink/source reported by the eight model countries. Figures are shown for calculations based on three alternative baselines and three alternative accounting periods of 2008-2012 (Table 4a,d,g), 2058-2062 (Table 4b,e,h) and 1990-2150 (Table 4c,f,i) are considered. Percentage changes in the carbon net sink/source have been calculated for each country according to the default calculation defined above in Table 4a-c, except that different accounting indices have been adopted for LULUCF (and where appropriate for HWP) as shown in the Figure. In Table 4d-f the '1990 value' baseline was used in calculations, while in Table 4g-i the '1990 projection' baseline was used. The trivial case of using the BAU projection itself as baseline in calculations for BAU is not shown.

Reported estimates of carbon net sink/source are highly sensitive to choice of baseline and in particular choice of LULUCF accounting index. The picture is extremely confusing when combined with a short (5 year) commitment and reporting interval (Table 4a,b,d,e,g,h). When viewed over long time intervals (Table 4c,f,i), reported estimates of carbon net sink/source under BAU appear less sensitive to choice of baseline (apart from the obvious trivial case of choosing BAU as baseline), and reported estimates of carbon net sink/source under BAU fall into two groups, depending on choice of accounting index. The first group of indices consists of those based on tonne-years or rental systems, which appear to understate fluctuations in the carbon net sink/source. In the case of tonne-year indices this may be due to their time-integrative nature. In the very long term tonne-year and rental indices tend to underplay sinks and indicate sources, mainly as a result of assumptions about capping of credits. Analysis based on consideration of BAU may not be a fair test of these indices. The second group of indices consists of real-time, one-off, and benchmark-type indices which give similar results, in particular with respect to relative ranking of different countries. However specific results reported for individual countries may vary significantly.

General observations

A number of extensions and improvements can be made to the analysis presented in this study. There is a clear need to verify whether the findings reported above are valid for scenarios other than BAU. More realism would be afforded if a greater range of countries was represented within the hypothetical world, if forests in different countries were represented, in particular countries for which R_i is close to or less than zero. The analysis may be oversimplified by because it uses only two forest carbon models to represent all forests in all countries, and a single model for patterns of wood utilisation in each country, while soil carbon dynamics are ignored. Elaboration of these aspects of the model may be needed to provide a complete test of differences between one-off and benchmark accounting indices.

Although the above analysis is based heavily on the provisions of the Kyoto Protocol, the approach to the analysis is valid in general and many of findings would apply to any accounting system that may be adopted by countries in support of the ultimate objective of the UNFCCC.

CONCLUSIONS

The findings of the above analysis may be summarised as follows:

1. Compared to fossil fuel emissions, construction of baselines for LULUCF and HWP is complicated, requiring a lot of assumptions about past, present and future LULUCF and HWP trade/utilisation.

2. It is questionable, however, whether very sophisticated assumptions would yield more reliable BAU projections than simple assumptions.

3. Even if BAU assumptions about LULUCF are kept very simple, resultant projections can be highly non-linear, with very large fluctuations and discontinuities in the predicted carbon net sink/source.

4. A five year commitment and reporting interval is extremely short relative to potential fluctuations in LULUCF/HWP carbon net sink/source.

5. Calculating percentage increases or reductions using net-net, gross-net and Article 3.7 rules all have potential problems. Although not perfect, adherence to Article 3.7 may in fact avoid the worst of these.

6. It may be necessary to allow for the carbon net sink/source in HWP as well as LULUCF if Article 3.7 is to be applied as written.

7. The Atmospheric flow method of allocating carbon net sink/source due to HWP is imbalanced and would result in an over-reporting of emissions. There is also a risk of double counting of emissions – as loss of forest carbon at time of harvest and then again as loss of wood-product carbon.

8. Adoption of either the Production, Stock Change or IPCC method of HWP allocation can result in differences in percentage changes reported that are as high as ±15%, although the different HWP accounting methods have only marginal influence on the relative ranking of the different countries in terms of reported percentage change in carbon net sink/source, particularly if estimates are accumulated over longer periods.

9. Reported estimates of carbon net sink/source are highly sensitive to choice of baseline and in particular choice of LULUCF accounting index. The picture is extremely confusing when combined with a short (5 year) commitment and reporting interval.

10. When viewed over long time intervals, reported estimates of carbon net sink/source under BAU may not be very sensitive to choice of baseline (apart from the obvious trivial case of choosing BAU as baseline).

11. When viewed over long time intervals, reported estimates of carbon net sink/source under BAU fall into two groups, depending on choice of accounting index:

Indices based on tonne-years or rental systems tend to understate fluctuations in the carbon net sink/source. In the case of tonne-year indices this may be due to their time-integrative nature. In the very long term tonne-year and rental indices tend to underplay sinks and indicate sources, mainly as a result of assumptions about capping of credits. Analysis based on consideration of BAU may not be a fair test of these indices.

Real-time, one-off, and benchmark-type indices give similar results, in particular with respect to relative ranking of different countries. However specific results reported for individual countries may vary significantly.

12. It is essential to test the sensitivity of the above conclusions to consideration of non-BAU scenarios.

13. It may be necessary to include more countries within the hypothetical world and also to model variations in forest carbon accumulation and wood utilisation. Soil carbon dynamics in response to LULUCF needs to be considered. The analysis needs to be validated by testing the sensitivity of the results to variation in these aspects of the model.

14. Although the above analysis is based heavily on the provisions of the Kyoto Protocol, the approach to the analysis is valid in general and many of findings would apply to any accounting system that may be adopted by countries in support of the ultimate objective of the UNFCCC.

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APPENDIX 1. DESCRIPTION OF METHODS FOR CALCULATING CARBON NET SINK/SOURCE DUE TO HARVESTED WOOD PRODUCTS (HWP)

IPCC 1996 Guideline Method for GHG Inventory

This effectively ignores carbon dynamics in HWP, by assuming that all wood harvested from forests decays in the year and by implication at the location of felling. This method has the advantage that the potentially difficult job of assessing emissions and removals due to HWP can be avoided.

Atmospheric Flow Method

Effectively this method treats HWP in the same manner as fossil fuel. Under this method, countries incur carbon emissions when wood products decay or are destroyed within national boundaries. For example, suppose that some trees were harvested in a stand in Sweden and imported into the UK. Sweden would not have to report an emission of carbon for the export of this wood, and the UK would not be able to claim any credit for the import of carbon. However the UK would have to report an appropriate emission of carbon for any losses from HWP due to decay or destruction. What is not clear, however, is whether an exporting country would have to report an emission for any loss of carbon stocks from the forest stand as a result of harvesting – this could lead to double counting or under reporting of emissions unless proper distinction was made between carbon in wood going into products and carbon emissions arising from decay of branches and stumps left behind.

Stock Change Method

Under this method HWP are treated in a similar manner to forests. Emissions and removals of carbon are calculated from the change in stocks of carbon both in the forest and within wood products pools within each country. For example, suppose again that some trees were harvested in a stand in Sweden and imported into the UK. In principle Sweden would have to report an emission of carbon due to any losses from the forest arising from harvesting, but could claim credits for any increases in carbon stocks in wood products. However Sweden would transfer these credits to the UK at time of export, since by implication the purchaser and owner of the harvested wood also owns any carbon in the wood. If carbon stocks could be shown to have increased in the UK as a result of such consumption of wood products then the UK could claim credit for equivalent carbon removals, however the UK would still have to report an appropriate emission of carbon for any losses from the wood products due to decay or destruction. This system clearly avoids the double counting problems that could potentially arise under the Atmospheric Flow Method, and treats trade in wood as trade in sequestered carbon rather than trade in carbon reserves.

Production Method

Under this method any carbon retained in harvested wood products remains attributed to the country where the timber was grown, even if it is exported. By the same token any emissions arising from the decay or destruction of these wood products is also attributed to the producer country.

APPENDIX 2. EVALUATION OF POTENTIAL IMPACTS OF ALTERNATIVE CARBON ACCOUNTING METHODOLOGIES FOR HARVESTED WOOD PRODUCTS IN THE UK

Global context

Before considering carbon stocks and fluxes associated with harvested wood products in the UK it may be appropriate to place the subject in a global context.

Experts have attempted to estimate the size of the carbon pool in wood products in the period 1990 to 2000 at the global scale and results range from 3 to 25 GtC, with the higher estimate regarded by its originator as 'optimistic'. The majority of the estimates are derived from accounting models that have not been validated and therefore should be treated with caution. In principle, carbon stocks could be measured by direct inventory, but only two research groups have made extensive use of the inventory approach (Alexander, 1997; Pingoud *et al*., 1996, 2000;). Extrapolation of these inventory-based country studies to the global scale gives an estimated global carbon stock at the lower end of the range indicated above.

Detailed analysis of current research estimates suggests the following interpretation. Carbon stocks in longer-lived wood products in primary and secondary use around the world may amount to about 2 to 3 GtC, although this estimate must be viewed as requiring further validation. Estimates including stocks in landfill are even more approximate, but current analyses suggest that total world carbon stocks in wood products and landfill are of order 10 GtC, perhaps as much as 25 GtC. This is equivalent to about 2 to 7 per cent of the carbon in biomass in world forests, and 1 to 2 per cent compared to carbon in forest biomass and soils under forests (Dixon *et al*., 1994). Evidence from inventory studies (Alexander, 1997; Pingoud *et al*., 1996, 2000) and also from studies based on accounting models (Winjum *et al*., 1998) suggests that the wood products carbon pool is currently expanding. Rough calculations based on the results of Alexander (1997) and Winjum *et al*. (1998) suggest that, world-wide, the wood products pool (including landfill) may be expanding at a rate in the range 0.01 to 0.1 GtC y^{-1}. This may be compared to the estimated net carbon flux from forests to the atmosphere of 0.9 GtC y^{-1} for the year 1990, primarily due to deforestation (Dixon *et al*., 1994). It is probable, therefore, that at present carbon stocks in wood products and any associated carbon sink are small compared to the contributions due to forests at the global scale.

Proposed accounting methodologies

Four alternative methods were proposed at a workshop held in Dakar as described in Appendix 1. The Atmospheric Flow, Stock Change and Production Methods all need to rely on some sort of modelling of flows of carbon through industrial and domestic sectors. The development of reliable, validated models in support of these methodologies represents a serious research challenge and raises issues concerning verifiability of reported estimates. In addition some system boundary issues remain unresolved, for example the status of wood products disposed to landfill sites.

Estimated impact on UK of alternative methodologies

Forest Research has been developing a computer model that can be used to evaluate alternative LULUCF and HWP carbon accounting methodologies, with particular focus on their likely impact at national and international level. The model uses summary data on forest areas and trade in wood products for different nations to estimate carbon emissions and removals that are likely to arise for different countries, depending on patterns of ARD and wood utilisation. Results for a range of example countries should be available for the agreed contract deadline in March. Results for the UK are presented in Tables A2.1 and A2.2.

Table A2.1 shows projections based on the four methodologies of the carbon sink/source due to HWP for the UK, at 5 year intervals, in the period 1990 to 2020. Removals and emissions of carbon due to disposal of carbon into landfill are not included, and in effect all carbon is assumed to be emitted at time of disposal to landfill. By definition the IPCC projection is zero. The projection for the Production methodology lies very close to the IPCC projection, because home-grown timber accounts for a relatively small proportion of the wood consumed in the UK. The estimated contribution of home-grown wood products is nevertheless smaller than some research might suggest and some validation may be necessary. Model analyses by Dr K. Pingoud (personal communication, 2000) indicate that wood products might account for a further 20% of carbon stocks over and above the stocks maintained in the forest stands that produced them. On the other hand the relative magnitude of the estimated contribution of home-grown timber in the UK seems to fit with the estimate based on the Stock Change Methodology. Under the Stock Change Methodology, harvested wood products make a significant contribution to the UK carbon sink when compared to the forest sink. The magnitude of this model projection in the year 1997 is comparable to an estimate derived by Alexander (1997) based on an inventory analysis of wood products in the UK. The projection of the carbon sink due to HWP reflects assumptions about future demand for wood products in the UK based on the analysis of Whiteman (1996). As would be expected, the impact of the Atmospheric Flow method on the projection is almost the opposite of the Stock Change Method. The precise timecourse of HWP carbon dynamics shown for the UK over this period depends on assumptions about rates of harvesting and patterns of utilisation in ensuing decades, so the results shown should be viewed as indicative only.

Table A2.2 presents alternative projections in which calculations for the Stock Change and Atmospheric Flow Methods include accounting for emissions and removals due to landfill. It should be stressed that these calculations, although based on the earlier quite detailed analysis of Alexander (1997), are highly speculative. The impact of including landfill in the calculations is quite dramatic, reflecting the historical disposal of wood-based materials to landfill and research results suggesting potentially very long retention times in landfill. The potential impact of policy measures discouraging landfill are not accounted for in these projections.

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Table A2.1

Carbon sink/source attributable to harvested wood products in the UK at 5 year intervals in the period 1990 to 2020

Year	Sink/source[1] (MtC y^{-1}) not including landfill			
	IPCC	Production	Stock Change	Atmospheric Flow
1990	0	-0.02	0.45	-2.64
1995	0	-0.02	0.43	-2.59
2000	0	-0.01	0.41	-2.69
2005	0	-0.01	0.39	-2.77
2010	0	-0.01	0.37	-2.83
2015	0	-0.01	0.35	-2.89
2020	0	-0.01	0.33	-2.94

[1] Positive estimates indicate sink while negative estimates indicate source.

Table A2.2

Carbon sink/source attributable to harvested wood products in the UK at 5 year intervals in the period 1990 to 2020

Year	Sink/source[1] (MtC y^{-1}) including landfill			
	IPCC	Production	Stock Change	Atmospheric Flow
1990	0	0.68	3.11	-0.76
1995	0	0.68	3.11	-0.92
2000	0	0.67	3.11	-1.09
2005	0	0.66	3.11	-1.26
2010	0	0.66	3.11	-1.43
2015	0	0.65	3.11	-1.59
2020	0	0.64	3.11	-1.75

[1] Positive estimates indicate sink while negative estimates indicate source.

APPENDIX 3. DESCRIPTION OF LULUCF ACCOUNTING INDICES

Real-time accounting

This index is formed simply of the raw LULUCF carbon net sink/source estimates produced by the CARBINE model for successive years.

One-off accounting

The ‘one-off’ or ‘one-time’ accounting approach (Maclaren, 2000) is an attempt to simplify the real-time approach an in particular to avoid perverse incentives and disincentives that may arise from short-term fluctuations in a real-time index. Instead of tracking annual fluctuations in the LULUCF carbon net sink/source, the one-off approach recognises that a change in land cover and/or land use generally results in a one-off change in carbon stocks on the land when viewed over long time scales. Under the one-off accounting approach, afforestation on bare ground would result in credit being awarded for an agreed estimate of the time-averaged, long-term change in carbon stock ultimately achieved through establishment of forest stands. This credit would be awarded in full at the time of inception of the afforestation programme, after which no further credits or debits would be accrued. By the same token, permanent loss of forest, for example by conversion to bare ground would result in an equivalent one-off debit being incurred in full at the time of clearance.

In this study, benchmark carbon stocks were assigned to non-forest land, old-growth forest and commercially productive forest as shown in Table 1. Values for old-growth forest and commercially productive forest were obtained from simulation results produced by CARBINE. Changes in carbon stocks resulting from changes in land classification were assumed to take place immediately.

Tonne-year accounting

The tonne-year approach to accounting has been proposed to support the establishment of commercial forest carbon sequestration projects with potentially finite duration. Tonne-year indices are imbalanced in that they give credit in each year that carbon stocks are established or maintained on an area of land, but no debits are incurred when carbon stocks are lost. Much of the theoretical elaboration of tonne-year indices is concerned with reconciling imbalanced accounting for LULUCF with strictly balanced accounting for emissions from fossil fuel consumption (Fearnside *et al.*, 2000; Chomitz, 1998; Tipper and de Jong, 1998, Moura-Costa and Wilson, 1999). Proposed adjustments to raw tonne-year indices include division by a time constant (referred to as equivalence time) and capping of the accumulation of tonne-year credits accrued by a particular project at the level achieved after a fixed duration. Although attempts have been made to provide these adjustments with a physical basis, these are in effect pragmatic attempts to relate and reconcile two approaches to accounting that are not strictly compatible. For this study a tonne-year accounting index was defined as shown in the following equation:

$$\chi_t = \frac{1}{\tau}\sum_{i=t_0}^{i=t}(c_i - c_0)$$

where χ_t is the credit awarded in year t (tC ha^{-1}), t_0 is the year in which a given forestry project or scheme is started, c_i is the carbon stock (tC ha^{-1}) in year i following establishment of the forestry project or scheme, c_0 is the initial carbon stock (tC ha^{-1})in year t_0, prior to establishment of the forestry project or scheme, τ is the equivalence time needed to convert a time-integrated sum of carbon stocks in units of tC-years ha^{-1} to an equivalent index in units of tC ha^{-1}. The value of τ was set equal to 100 years in this study, also accumulation of χ_t was capped at the value accrued after 100 years from establishment in year t_0.

Application of the above equation to the model countries in this study required assumptions to be made about assigning of t_0 to forest areas. For simplicity, t_0 was set equal to the year of establishment for all newly created forest forest areas. Felling and regeneration of commercial forest stands was not regarded as creation of new forest and so t_0 was not reset to the new time of establishment in cases involving regeneration following clear fell. Tonne-year credits were calculated for all forest areas starting from year zero.

Advance tonne-year accounting

Advance tonne-year accounting has been proposed to reward commercial forestry projects that make an advance commitment to maintain carbon stocks for a given duration (Jackson, 1999). In this study this was represented by an index similar to the basic tonne-year index defined above, except that it was assumed that forestry projects would accrue the first 40 years of tonne-year credits in full at time of establishment. No further credit would be accrued for the 40 year period, however maintenance of the carbon stocks beyond the 40 year period would attract further credits up to the capped value attained after 100 years duration.

Rental accounting

Rental accounting has been proposed as a way to permit credit to be given for short-term commitments to forest carbon sequestration projects, while avoiding the complexity of calculations and supporting assumptions needed for accounting indices based on the tonne-year approach (Fruit and Marland, 2000). In this approach, credit may be claimed for carbon sinks in newly created forests, however after a fixed duration, no further commitment is made to maintenance of the forest carbon stocks, and accordingly the credits must be rescinded. Although, arguably, rental accounting is more appropriate for application at the project level, it was decided to include evaluation of a system of rental accounting in this study, as an illustration of what might happen if countries participating in the Kyoto Protocol agreed to inclusion of sinks but only on a short-term basis.

In this study, the rental accounting index was calculated for all newly created forest areas, and was calculated from carbon stock changes arising since time of establishment (t_0). Stock changes over a fixed 40 year duration from year t_0 were calculated and the resultant carbon sinks/sources derived as for the real-time index. Any credits accumulated during the 40 year period as a result of increases in forest carbon stocks were balanced at the end of the period by an equivalent debit. Beyond the 40 year period stock changes in the forest areas were ignored.

Benchmark accounting

Benchmark accounting (Kirschbaum *et al*. 2001) has been proposed with the aim of making LULUCF accounting as simple and cheap as possible, and with the particular aim of avoiding technically complex procedures for measuring and monitoring of LULUCF carbon net sinks/sources. It is similar in approach to one-off accounting, except that broad ‘benchmark values’ are used rather than detailed model-based estimates for assigning ultimate carbon stocks to different land cover and land use types. In addition, some versions of benchmark accounting may involve broad assumptions about the rate of accumulation of ultimate carbon stocks, for example a change in ultimate carbon stocks due to creation of a forest on bare ground may be assumed to take place over an arbitrary period following establishment.

In this study, benchmark carbon stocks were assigned to non-forest land, old-growth forest and commercially productive forest as shown in Table 1. These values were obtained by roughly rounding the estimates used in one-off accounting. Increases in carbon stocks resulting from a change of land classification were assumed to accumulate linearly over a period of 50 years, however decreases in carbon stocks were assumed to take place immediately.

Simplified benchmark accounting

This accounting approach was similar to the benchmark accounting approach described above except that all changes in carbon stocks resulting from changes in land classification were assumed to take place immediately. In effect this accounting index is identical to the one-off accounting index except that roughly rounded benchmark values for carbon stocks are used.

Table 1 Description of eight model countries in terms of land area, forest area and fossil fuel consumption

	Circle	**Diamond**	**Oblong**	**Oval**	**Pentagon**	**Star**	**Trapezium**	**Triangle**
Land area (kha)	90 000	30 000	30 000	900 000	900 000	800 000	900 000	20 000
Total forest area (kha)	36 000	9 000	21 000	540 000	180 000	40 000	270 000	2 000
Exploited forest area (kha)	500	1 000	20 000	15 000	167 000	17 000	117 000	1 800
Unexploited forest area (kha)	35 500	8 000	1 000	525 000	1 300	23 000	153 000	200
Total forest as percentage of land area	40	30	70	60	20	5	30	10
Net change in total forest area (%yr^{-1})	-1.0	0.6	-0.1	-0.5	0.3	0.0	0.0	0.5
Fossil fuel CO_2 emissions (Mt C)	1	10	15	100	1500	100	150	150

Table 2 Impact of adopting net-net, gross-net or strict Article 3.7 on reported percentage emission increase or reduction

(a) Period 2008 - 2012

Interpretation	Country							
	Star	**Oval**	**Trapezium**	**Oblong**	**Triangle**	**Diamond**	**Circle**	**Pentagon**
Net-net	7	1	43	-29	-9	-52	1	10
Gross-net	24	>100	>100	87	-12	-73	>100	-6
Strict interpretation	7	1	43	-29	-12	-73	1	-6

(b) Period 1990-2150

Interpretation	Country							
	Star	**Oval**	**Trapezium**	**Oblong**	**Triangle**	**Diamond**	**Circle**	**Pentagon**
Net-net	-14	-33	-5	-59	-4	41	-69	7
Gross-net	-1	>100	68	7	-7	-20	>100	-9
Strict interpretation	-14	-33	-5	-59	-7	-20	-69	-9

Table 3 impact of adopting HWP calculation methods on reported percentage emission increase or reduction

(a) Period 2008-2012

Interpretation	**Country**							
	Star	**Oval**	**Trapezium**	**Oblong**	**Triangle**	**Circle**	**Diamond**	**Pentagon**
No wood products	16	2	49	-25	0	-61	1	6
Production	14	2	52	-28	0	-75	1	-1
Stock change	7	1	43	-29	-12	-73	1	-6
Atmospheric flow	15	3	41	-19	53	-8	1	59

(b) Period 1990-2150

Interpretation	**Country**							
	Star	**Oval**	**Trapezium**	**Oblong**	**Triangle**	**Circle**	**Diamond**	**Pentagon**
No wood products	-10	-32	-2	-57	-1	-14	-69	-3
Production	-5	-32	0	-49	-1	-27	-69	-6
Stock change	-14	-33	-5	-59	-7	-20	-69	-9
Atmospheric Flow	4	-28	6	-43	65	52	-68	63

Table 4(a) Impact of choice of baseline and accounting index on reported emission increase or reduction

Period 2008-2012, zero baseline

Accounting index name	**Country**							
	Star	**Oval**	Trapezium	**Oblong**	**Triangle**	**Diamond**	**Circle**	**Pentagon**
Real time	7	1	43	-29	-12	-73	1	-6
One-off	1	0	0	-65	-8	-51	0	-10
Tonne-year	0	0	0	<-100	-6	-18	0	-13
Advance tonne-year	0	0	0	>100	-6	-19	0	-12
Rental	0	0	0	23	1	-41	0	6
Benchmark	2	0	1	-67	-9	-41	0	-15
Simplified benchmark	1	0	0	-62	-7	-49	0	-9

Table 4(b) Impact of choice of baseline and accounting index on reported emission increase or reduction

Period 2008-2012, 1990 value baseline

Accounting index name	Country							
	Star	Oval	Trapezium	Oblong	Triangle	Diamond	Circle	Pentagon
Real time	7	1	30	-19	-19	-40	1	-2
One-off	1	0	0	-65	-8	-51	0	-10
Tonne-year	0	0	0	19	0	-10	0	0
Advance tonne-year	0	0	0	19	-1	-14	0	-1
Rental	0	0	0	23	1	1	0	6
Benchmark	1	0	1	-47	2	-15	0	4
Simplified benchmark	1	0	0	-62	-7	-49	0	-9

Table 4(c) Impact of choice of baseline and accounting index on reported emission increase or reduction

Period 2008-2012, 1990 projection baseline

Accounting index name	**Country**							
	Star	**Oval**	**Trapezium**	**Oblong**	**Triangle**	**Diamond**	**Circle**	**Pentagon**
Real time	-4	0	-21	-77	-2	-46	0	-5
One-off	1	0	0	-65	-8	-51	0	-10
Tonne-year	-1	-1	-5	10	0	-3	-3	0
Advance tonne-year	0	0	0	19	-1	-14	0	-1
Rental	-14	-13	-64	-87	-1	-45	-41	-3
Benchmark	-6	-1	-11	-59	-2	-19	0	-3
Simplified benchmark	1	0	0	-62	-7	-49	0	-9

Table 4(d) Impact of choice of baseline and accounting index on reported emission increase or reduction

Period 2058-2062, zero baseline

Accounting index	**Country**							
	Star	**Oval**	**Trapezium**	**Oblong**	**Triangle**	**Diamond**	**Circle**	**Pentagon**
Real time	-20	0	11	-59	-7	60	-99	-1
One-off	-19	0	1	-65	2	96	-99	2
Tonne-year	4	1	3	<-100	1	-23	8	5
Advance tonne-year	6	1	3	>100	1	-8	23	3
Rental	16	0	0	1	0	>100	42	0
Benchmark	-20	1	2	-62	5	3	-99	13
Simplified benchmark	-17	0	1	-62	1	89	-99	1

Table 4(e) Impact of choice of baseline and accounting index on reported emission increase or reduction

Period 2058-2062, 1990 value baseline

Accounting index	**Country**							
	Star	**Oval**	**Trapezium**	**Oblong**	**Triangle**	**Diamond**	**Circle**	**Pentagon**
Real time	-18	0	7	-38	-17	23	-98	-11
One-off	-19	0	1	-65	-7	-6	-99	-9
Tonne-year	4	1	1	44	1	-22	5	5
Advance tonne-year	5	1	1	48	0	-20	15	1
Rental	16	0	0	1	0	95	42	0
Benchmark	-16	1	2	-44	5	3	-98	11
Simplified benchmark	-17	0	1	-62	-6	-5	-99	-8

Table 4(f) Impact of choice of baseline and accounting index on reported emission increase or reduction

Period 2058-2062, 1990 projection baseline

Accounting index	Country							
	Star	Oval	Trapezium	Oblong	Triangle	Diamond	Circle	Pentagon
Real time	-18	0	-10	-59	-6	26	-99	-7
One-off	-19	0	1	-65	-7	-6	-99	-9
Tonne-year	-8	-9	-39	-23	-2	-19	-22	-4
Advance tonne-year	-1	-5	-25	3	-2	-14	-1	-4
Rental	16	0	0	1	0	53	42	0
Benchmark	-34	-3	-27	-74	-6	-23	-99	-9
Simplified benchmark	-17	0	1	-62	-6	-5	-99	-8

Table 4(g) Impact of choice of baseline and accounting index on reported emission increase or reduction

Period 1990-2150, zero baseline

Accounting index	**Country**							
	Star	**Oval**	**Trapezium**	**Oblong**	**Triangle**	**Diamond**	**Circle**	**Pentagon**
Real time	-14	-33	-5	-59	-7	-20	-69	-9
One-off	-12	-32	-14	-64	-5	-16	-69	-7
Tonne-year	8	3	10	<-100	-5	-19	26	-9
Advance tonne-year	9	3	19	>100	-5	-17	29	-8
Rental	3	3	12	7	0	2	8	2
Benchmark	-12	-32	-18	-63	-6	-20	-69	-9
Simplified benchmark	-11	-32	-13	-61	-5	-15	-69	-7

Table 4(h) Impact of choice of baseline and accounting index on reported emission increase or reduction

Period 1990-2150, 1990 value baseline

Accounting index	**Country**							
	Star	**Oval**	**Trapezium**	**Oblong**	**Triangle**	**Diamond**	**Circle**	**Pentagon**
Real time	-13	-32	-3	-38	-14	13	-68	-5
One-off	-12	-32	-14	-64	-5	-16	-69	-7
Tonne-year	6	2	4	40	2	-11	14	5
Advance tonne-year	7	3	8	49	1	-12	19	2
Rental	3	3	12	7	0	44	8	2
Benchmark	-10	-31	-13	-44	5	6	-68	10
Simplified benchmark	-11	-32	-13	-61	-5	-15	-69	-7

Table 4(i) Impact of choice of baseline and accounting index on reported emission increase or reduction

Period 1990-2150, 1990 projection baseline

Accounting index	**Country**							
	Star	**Oval**	**Trapezium**	**Oblong**	**Triangle**	**Diamond**	**Circle**	**Pentagon**
Real time	-19	-33	-34	-73	-5	-15	-69	-7
One-off	-12	-32	-14	-64	-5	-16	-69	-7
Tonne-year	-5	-8	-38	-30	-2	-12	-13	-4
Advance tonne-year	-1	-4	-23	-6	-2	-12	-1	-4
Rental	0	0	0	-14	0	0	0	0
Benchmark	-25	-34	-37	-69	-5	-15	-69	-6
Simplified benchmark	-11	-32	-13	-61	-5	-15	-69	-7

Figure 1(a) Projected change in forest cover for country Pentagon

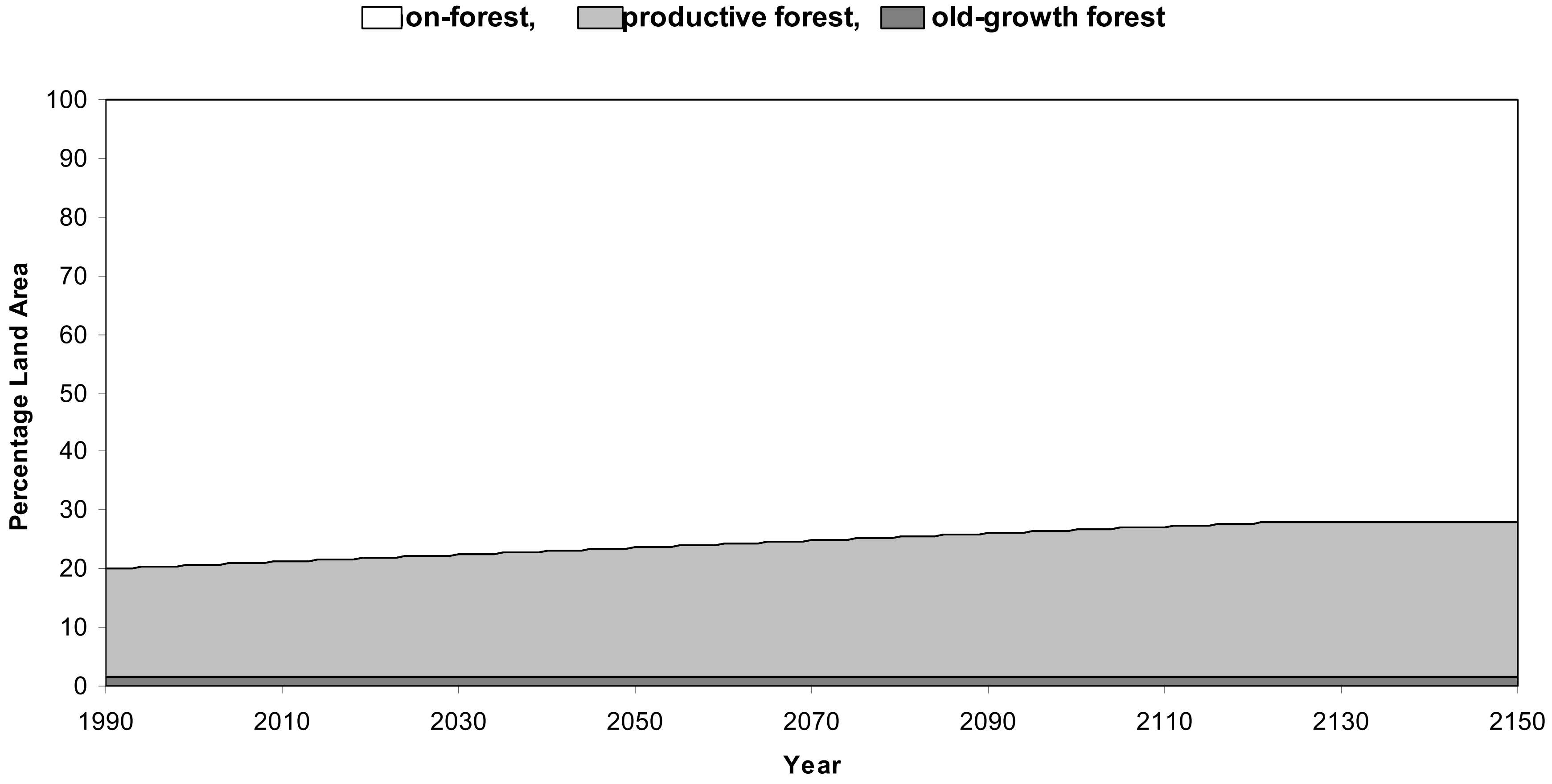


Figure 1(b) Projected change in forest cover for country Oblong

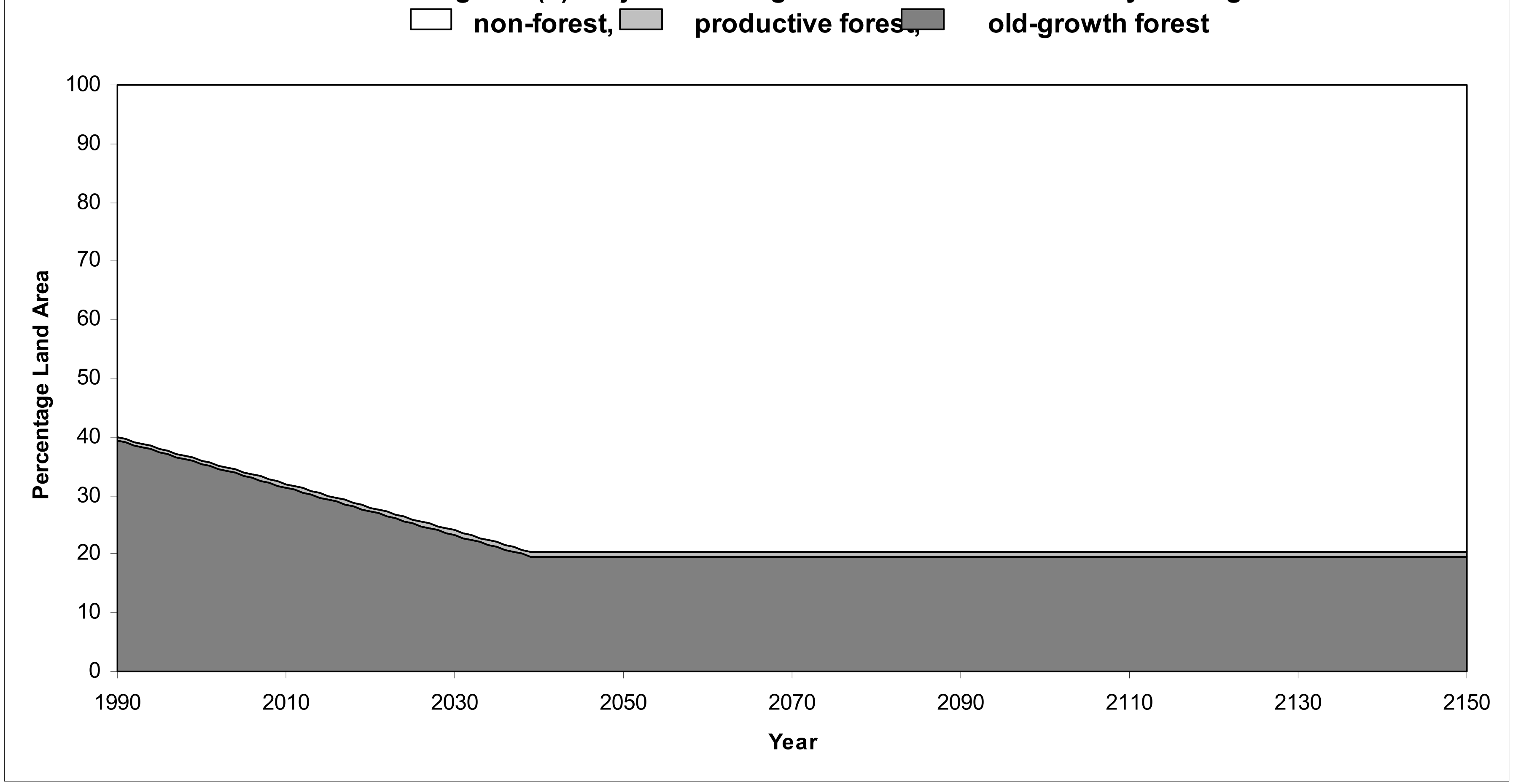


Figure 1(c) Projected change in forest cover for country Diamond

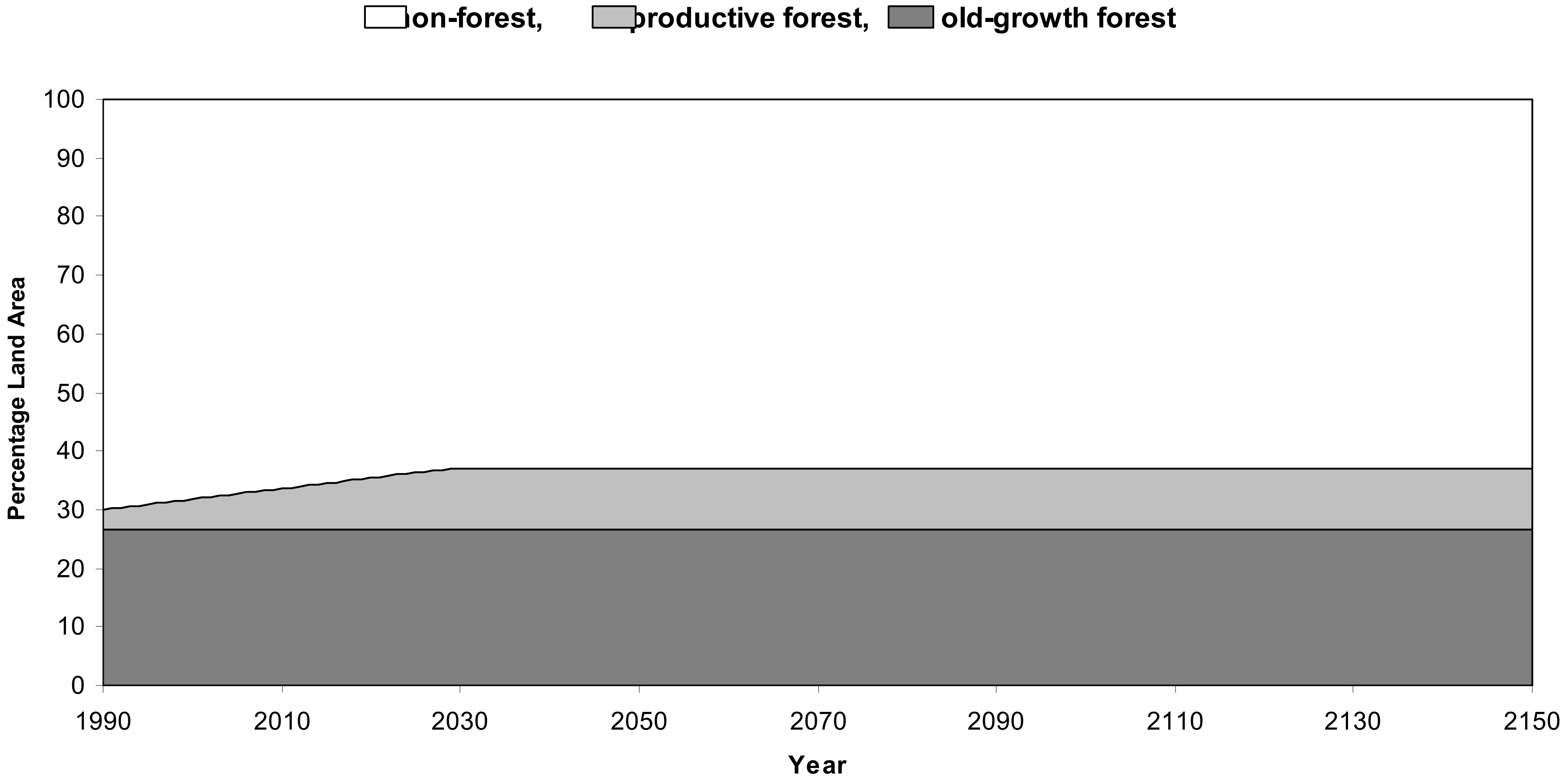


Figure 1(d) Projected change in forest cover for country Triangle

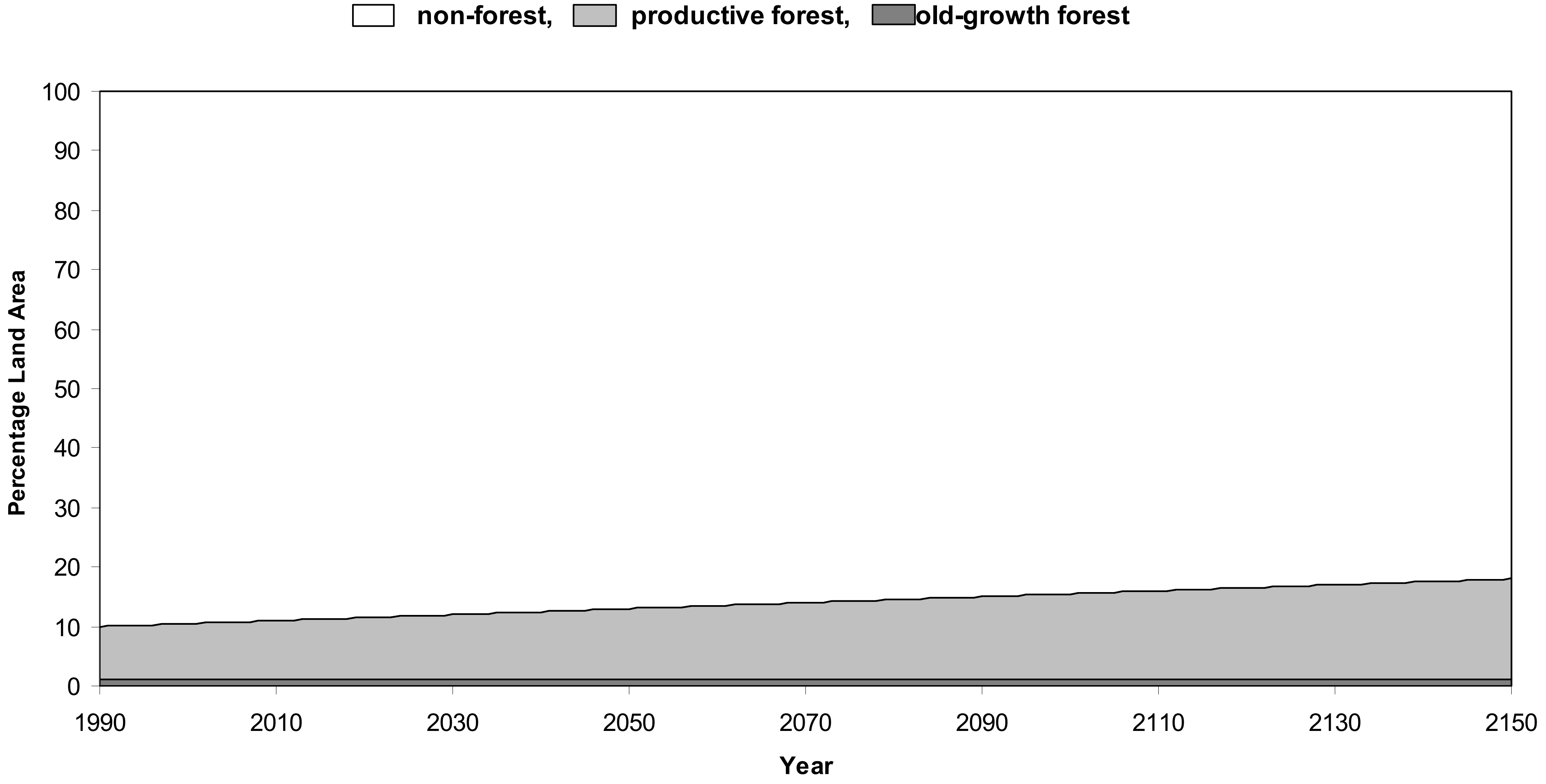
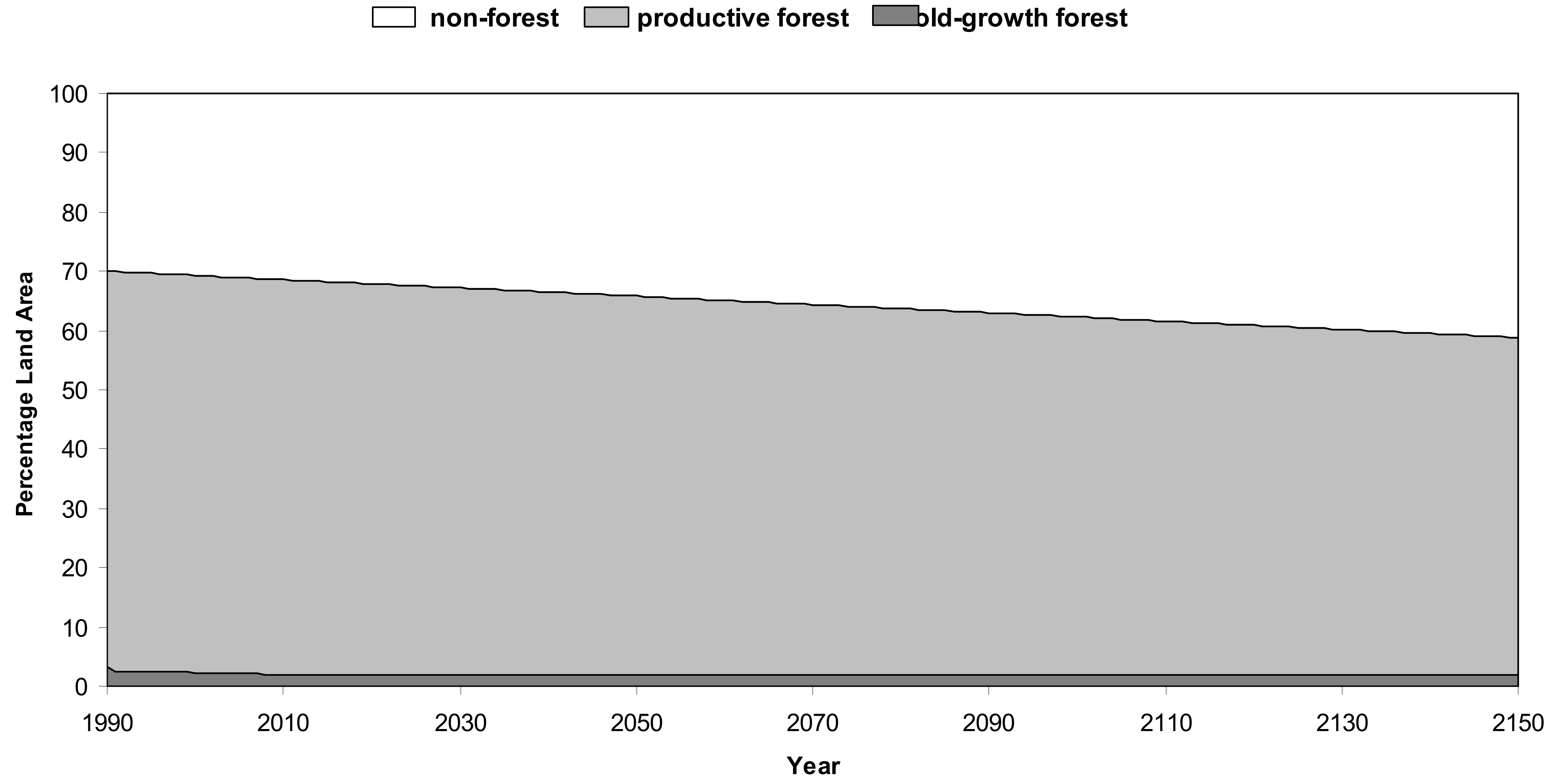


Figure 1(e) Projected change in forest cover for country Oblong



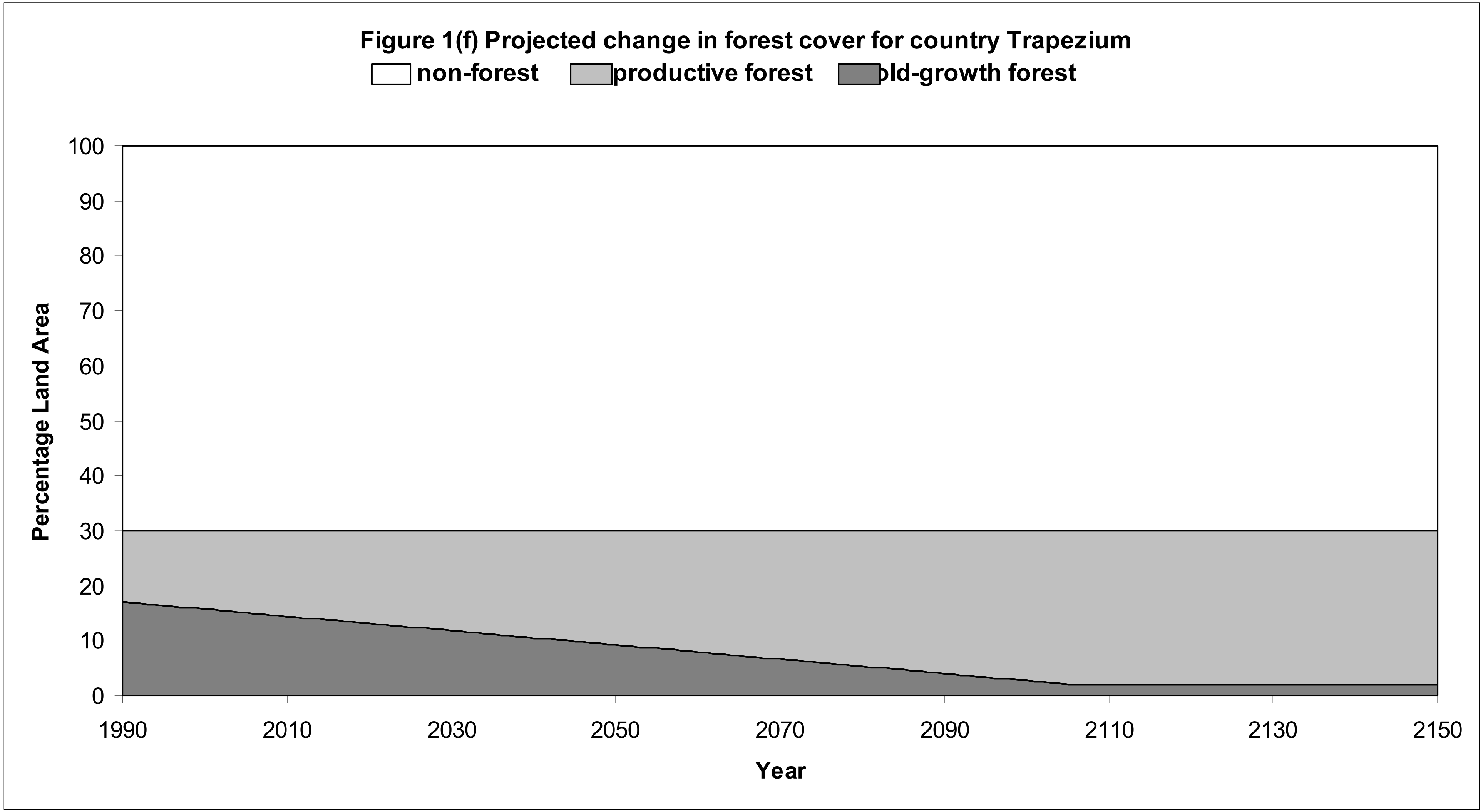


Figure 1(f) Projected change in forest cover for country Trapezium

Figure 1(g) Projected change in forest cover for country Oval

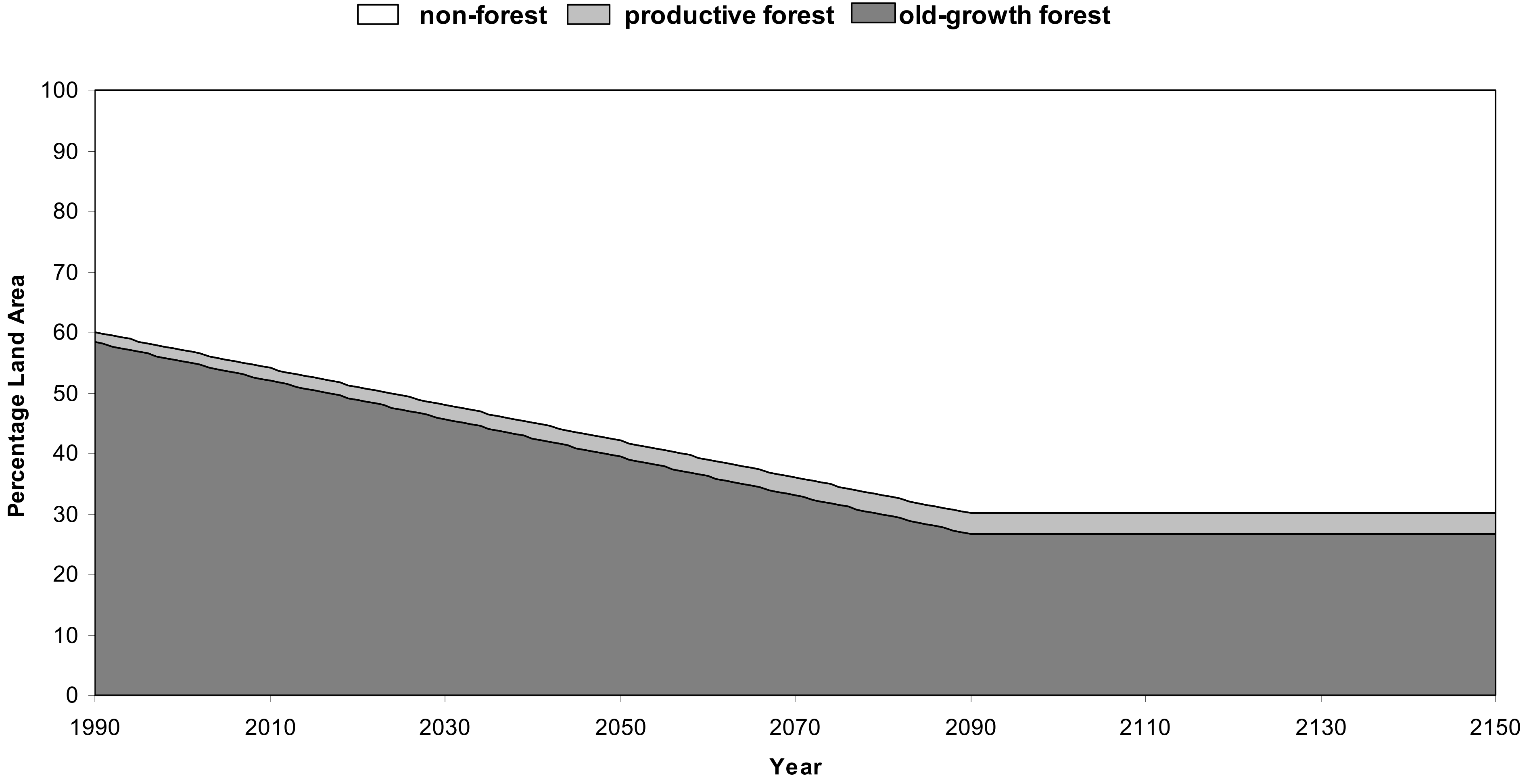


Figure 1(h) Projected change in forest cover for country Star

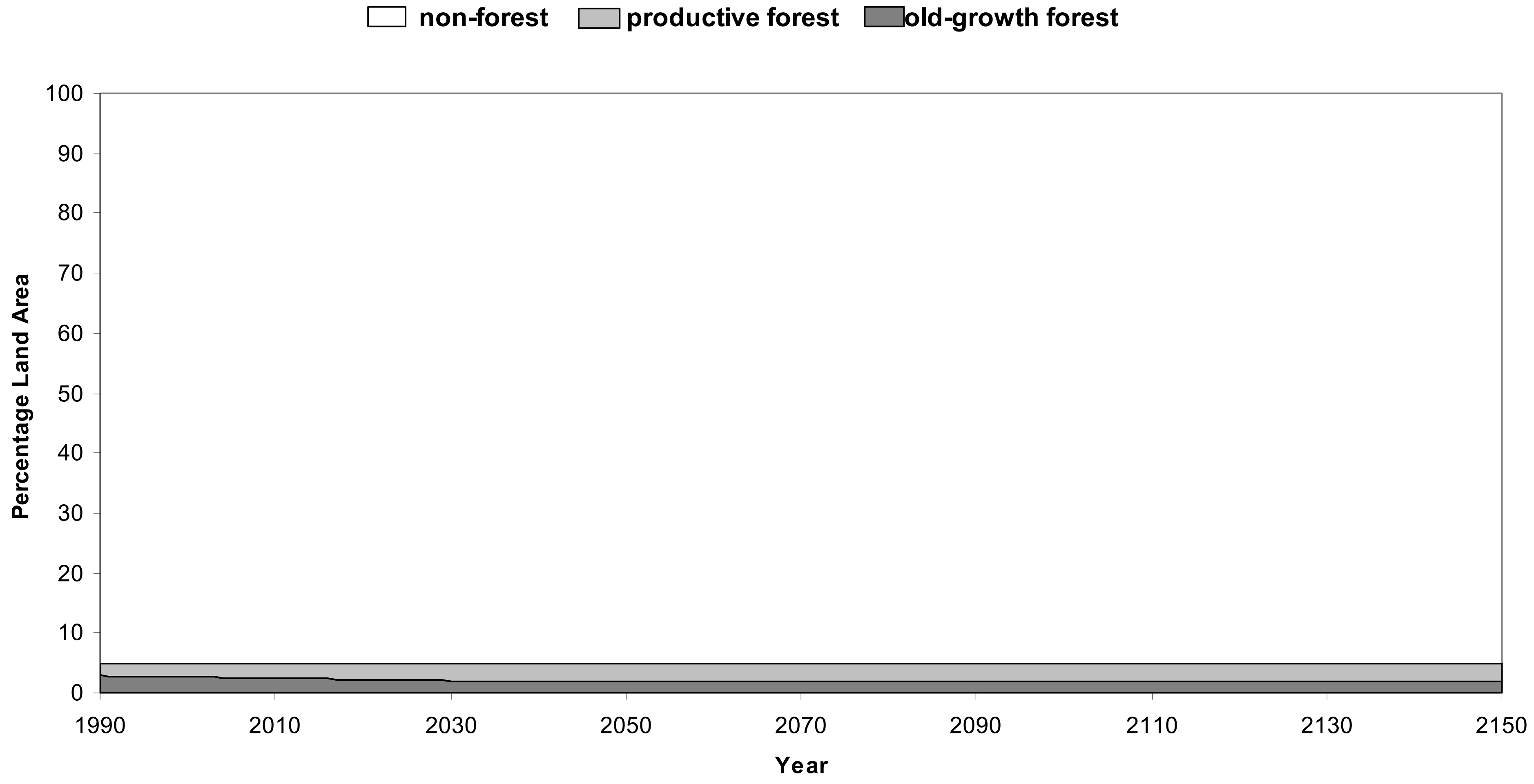


Figure 2 Projected carbon net sink/source under BAU for country Triangle (negative values indicate sink)

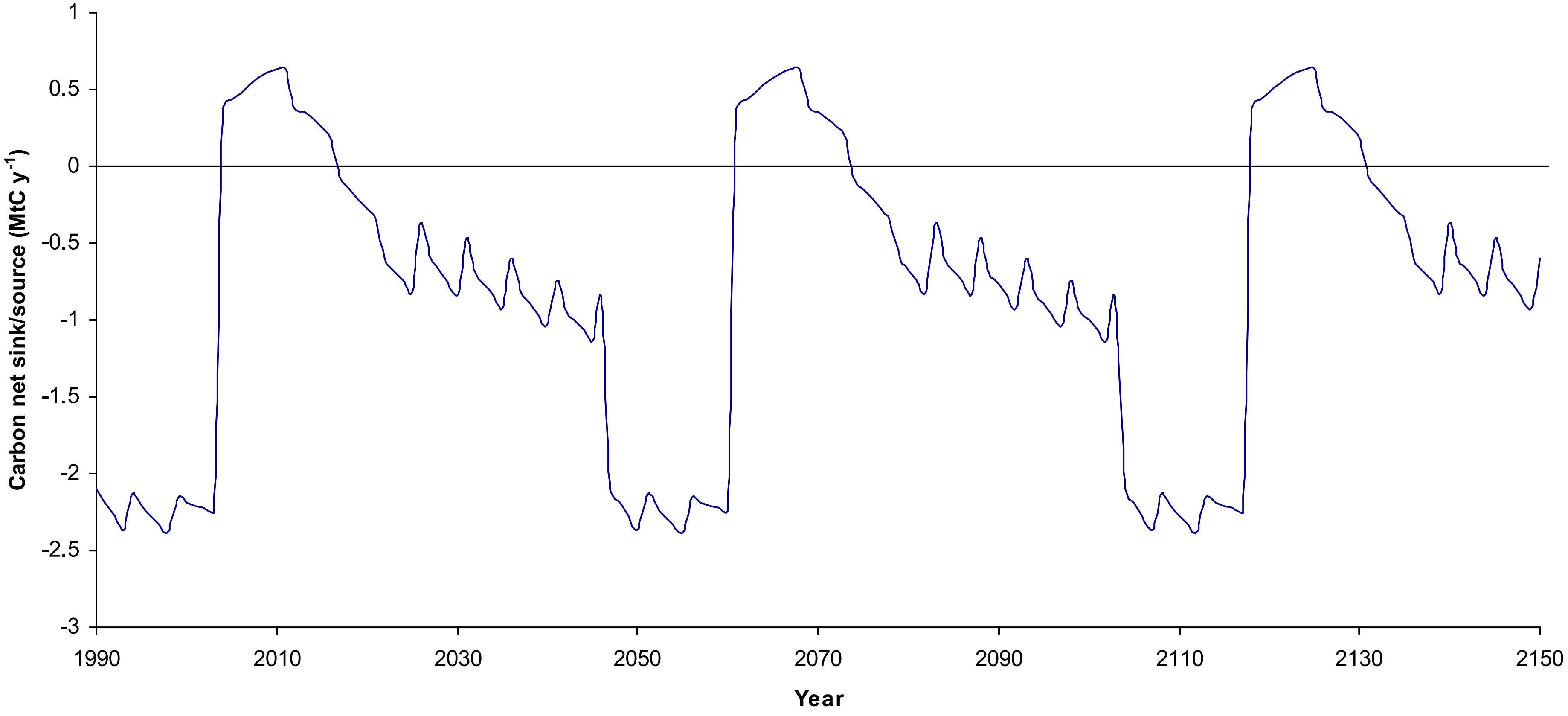


Figure 3 Projected HWP carbon net sink/source for country Triangle (Negative values indicate sink)

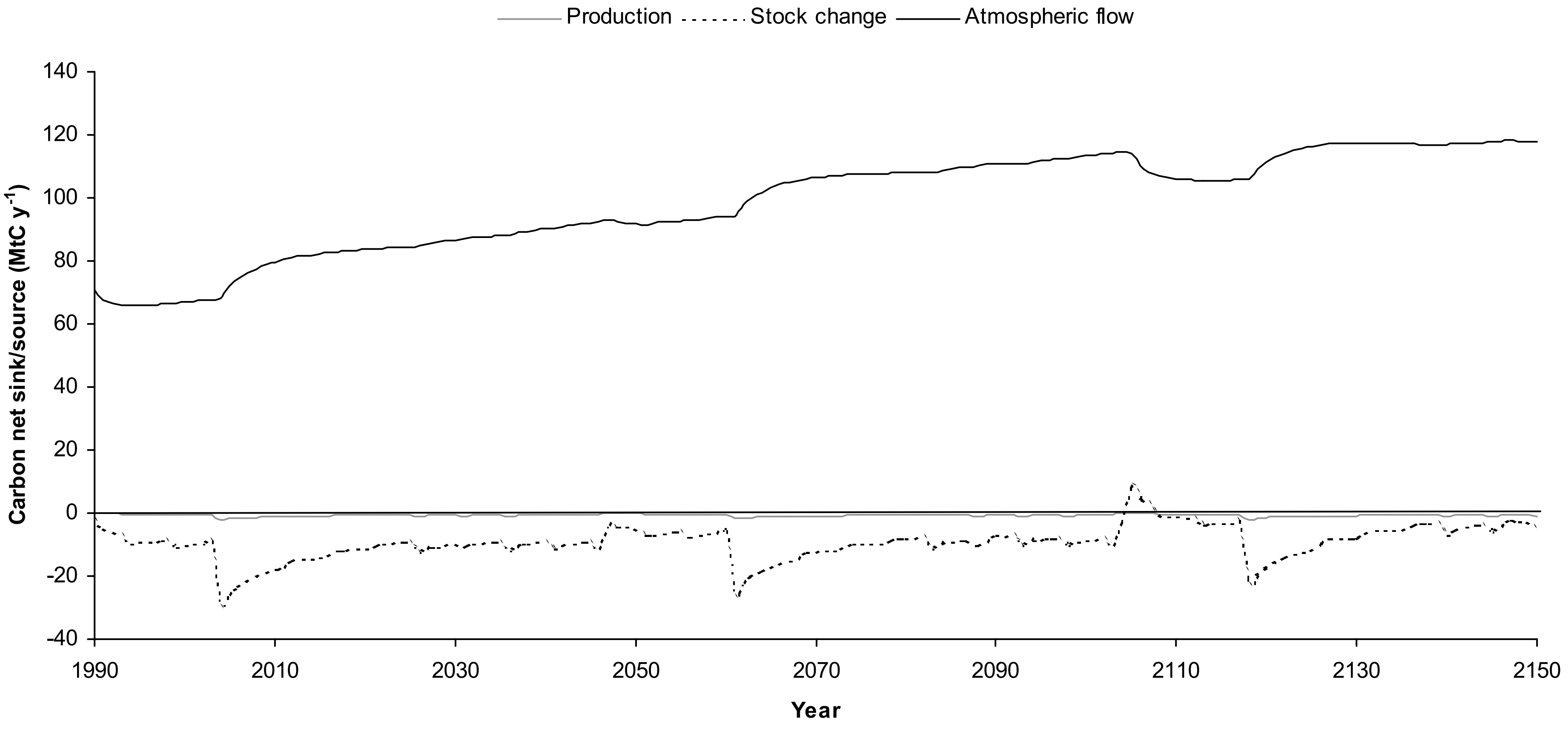


Figure 4 (a) Projected change in carbon net sink/source for country Pentagon

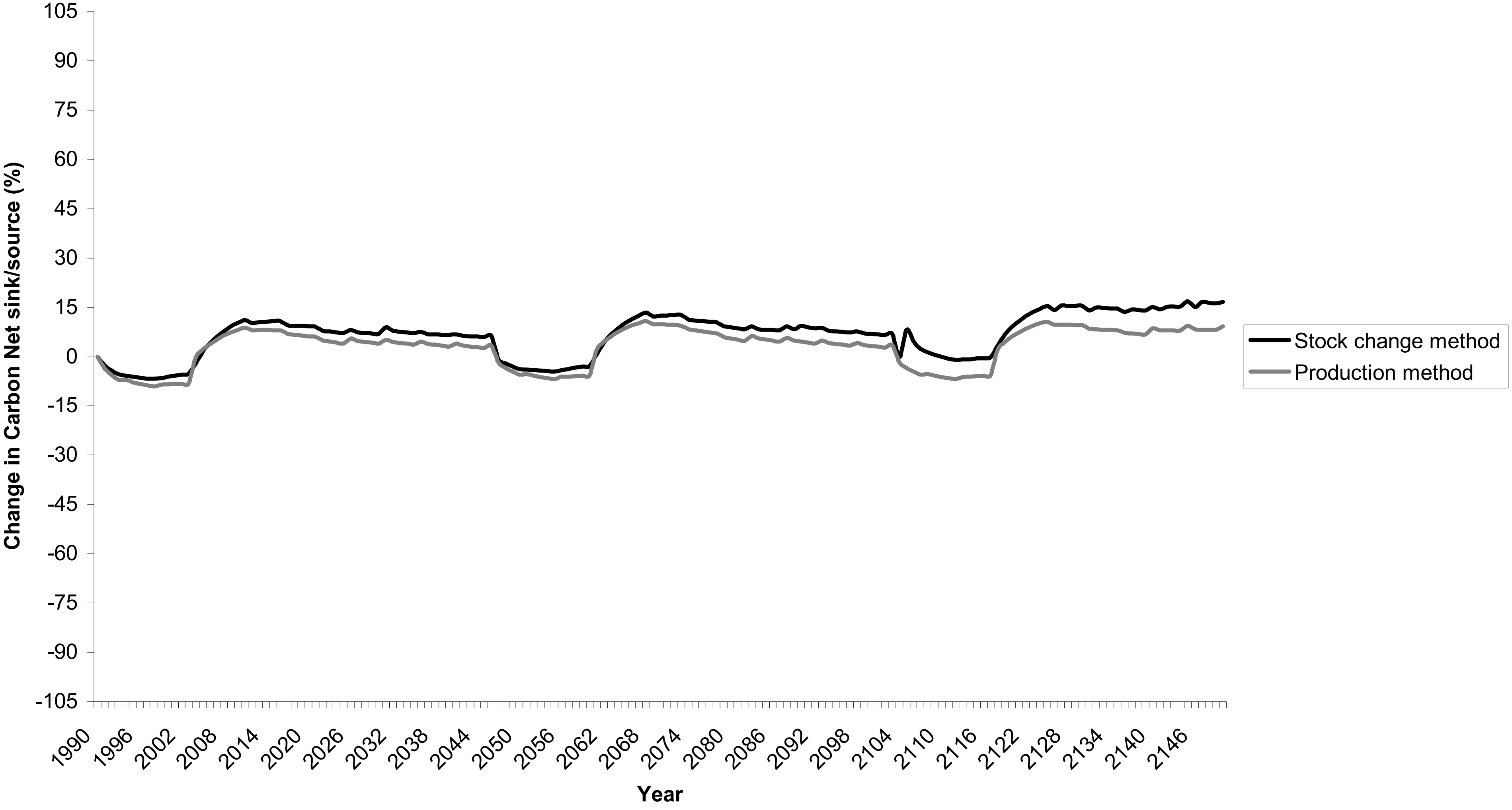


Figure 4 (b) Projected change in carbon net sink/source for country Circle

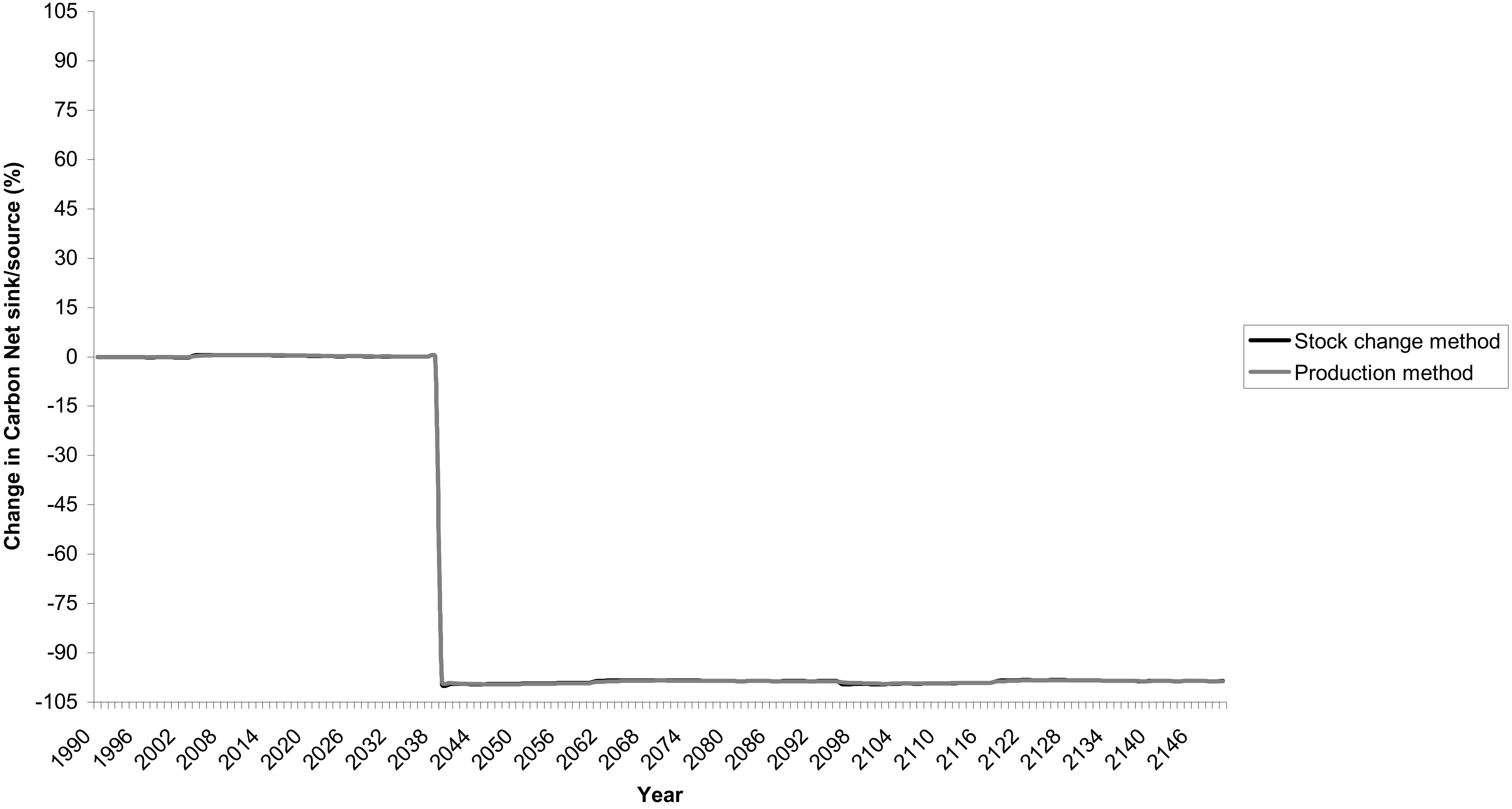


Figure 4 (c) Projected change in carbon net sink/source for country Diamond

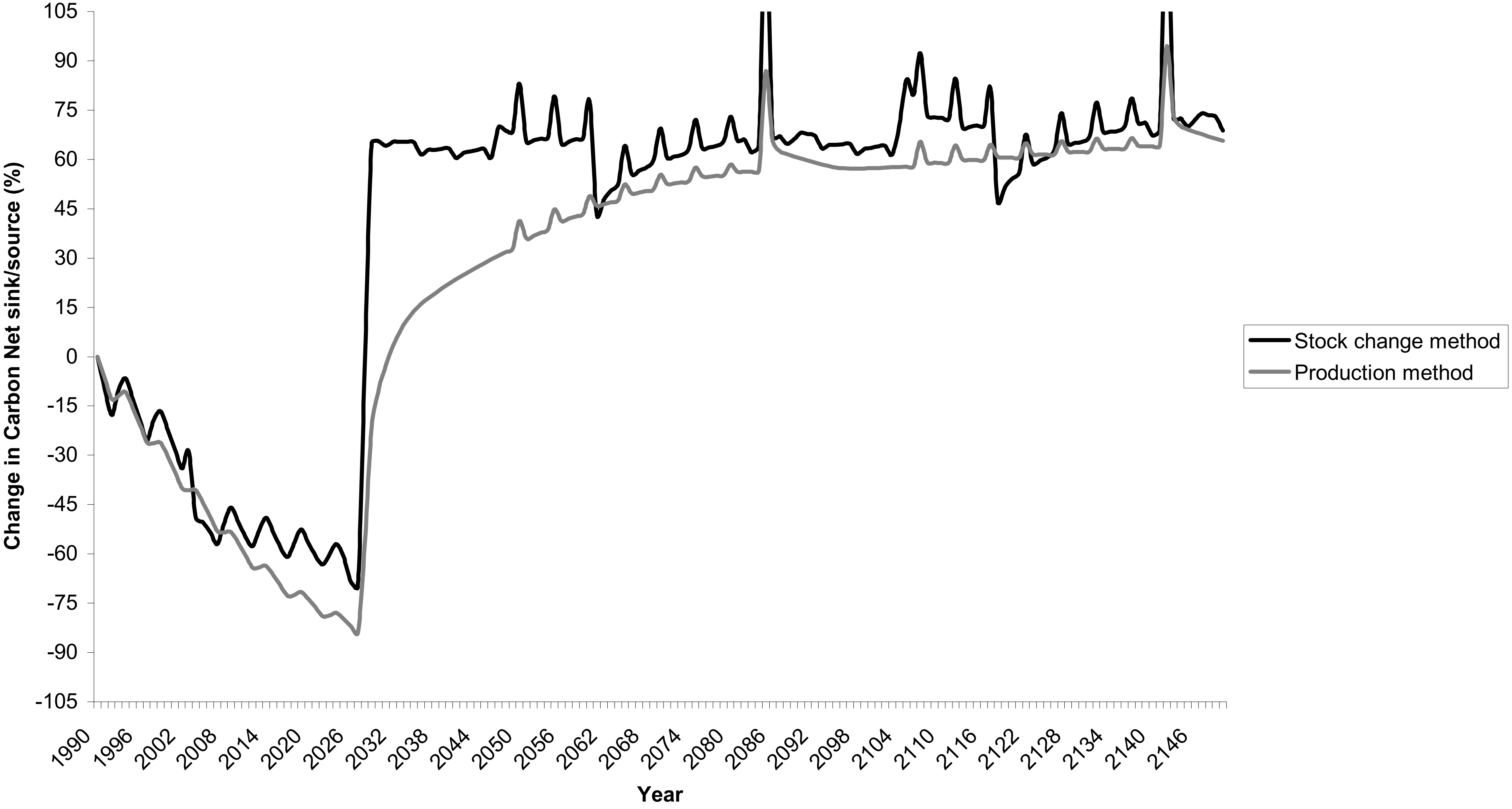


Figure 4 (d) Projected change in carbon net sink/source for country Triangle

Figure 4 (e) Projected change in carbon net sink/source for country Oblong

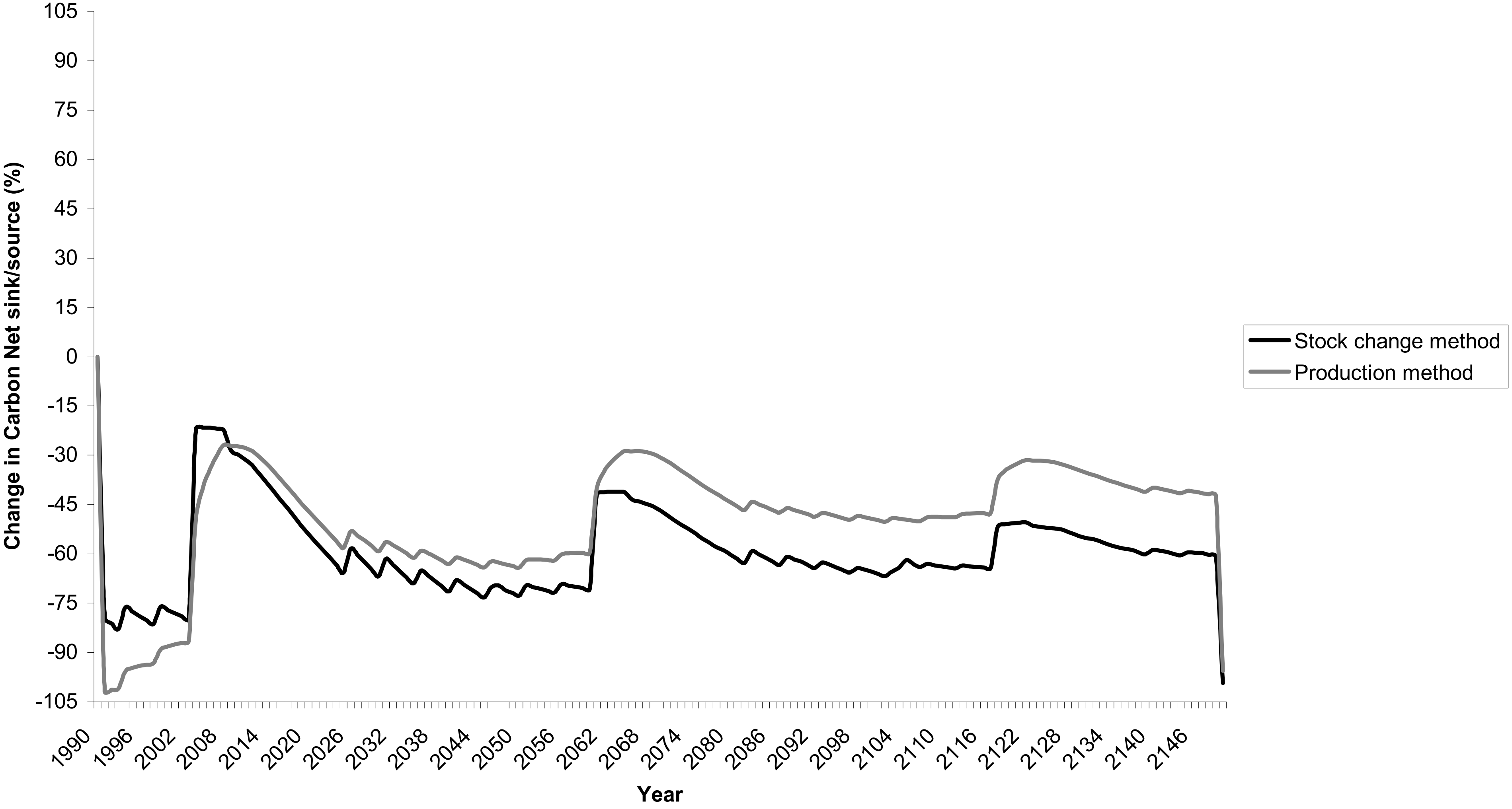


Figure 4 (f) Projected change in carbon net sink/source for country Oval

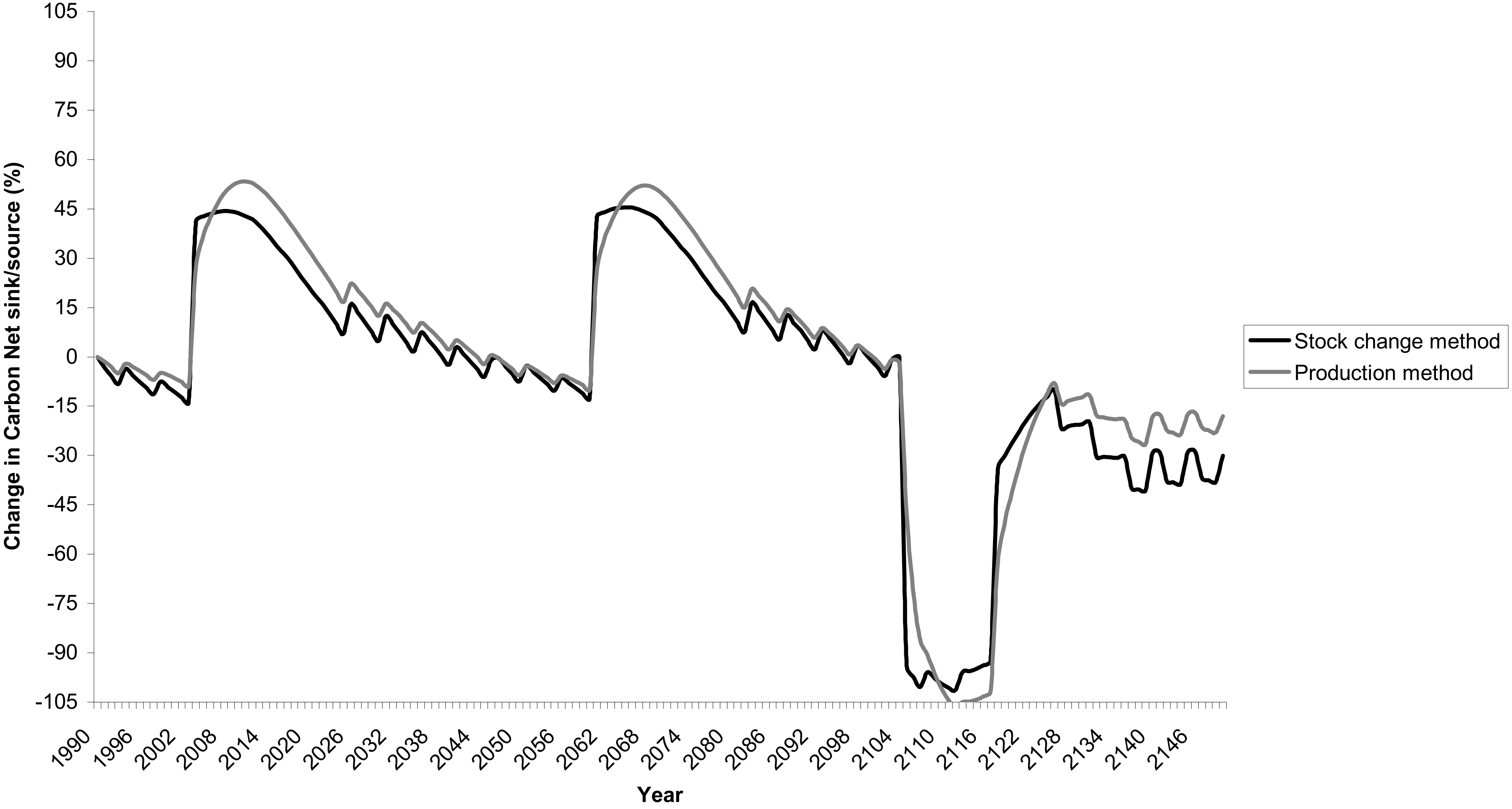


Figure 4 (g) Projected change in carbon net sink/source for country Star

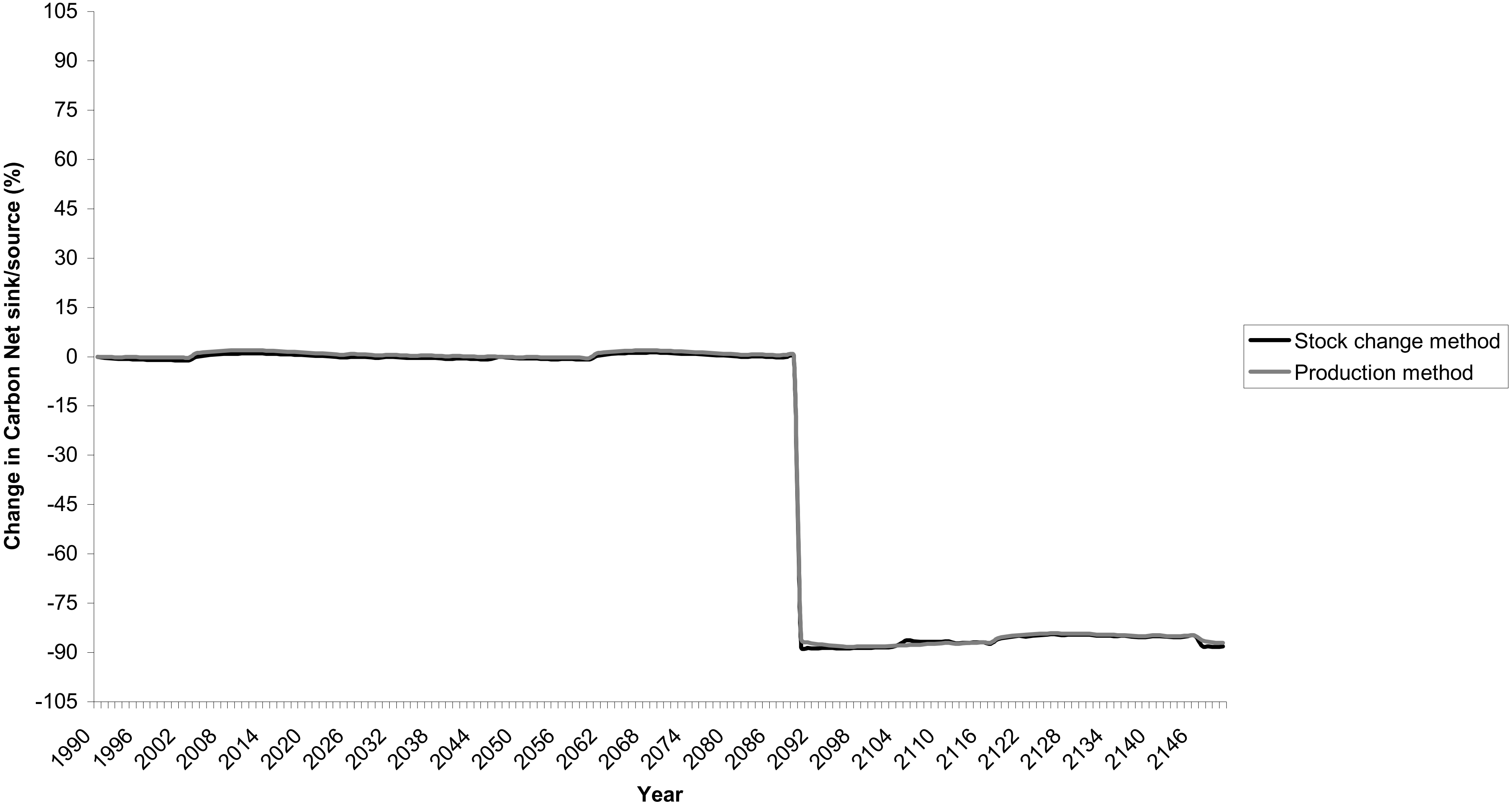


Figure 4 (h) Projected change in carbon net sink/source for country Trapezium