DOCTOR OF PHILOSOPHY

The application of spatial data in forest ecology and management; windthrow, carbon sequestration and climate change

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THE APPLICATION OF SPATIAL DATA IN FOREST ECOLOGY AND MANAGEMENT; WINDTHROW, CARBON SEQUESTRATION AND CLIMATE CHANGE

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DEDICATION

"To my beloved parents: Mrs Meherunnessa Rahman and Mr A.K.M. Moksudur Rahman, my wife Selina Amin Shila, who took over my family responsibilities during this study and the people of Bangladesh who sponsored me for this study."

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ABSTRACT

The overall aim of this study was to analyse the contribution of spatial data and GIS in strategic forest management at a regional planning level considering topical issues: windthrow, carbon sequestration and climate change. It also recommends how the methodologies might be transferred to other countries such as Bangladesh.

A macro-based geographical information system (GIS) is proposed as a suitable tool for modelling the interaction between wind and forest areas. Using the forest area of the Snowdonia National Park in North Wales, UK (affected by endemic windthrow) as the study area, land use, soil and windiness (**D**etailed **A**spect **M**ethod of **S**coring of the Forestry Commission of Great Britain) data were incorporated within a GIS. Shapes of forest patches were estimated through FRAGSTATS statistical software and placed in a GIS to combine the patch shape contributions with windiness. Four scenarios were generated from four combinations of patch shape, soil class and leaf presence in winter with the DAMS score to analyse the performance of the GIS in the integration of spatial data and techniques.

A geographical information system is used to combine and analyse spatial data. Forest site factors: soil, elevation and exposure to wind were considered with yield class prescribed by Pyatt (1977) and local expert advice (Stevens, 2001) with respect to soil classes. **A**djusted **y**ield **c**lasses (AYC) for the conifer plantations of the study area (Snowdonia National Park) were selected and validated to estimate the organic carbon in the organic carbon model. A GIS-Spreadsheet organic carbon model, to estimate the organic carbon stock of the woodland, was presented considering tree, litter and soil to a depth of one metre. The *Willis-Price* tree carbon model (Price, 2001) was used to estimate the carbon stock of the woodland. Published data were used to estimate the litter organic carbon and local expert advice and published data for the soil organic carbon to a depth of one metre. Sites which would fix an organic carbon stock as great as the conifer (*Picea sitchensis*) if the sites were replaced by the broadleaf species oak (*Quercus* spp.) were selected. The results of the study revealed that **y**ield **c**lass 02, 04 and 06 of oak enabled the fixing of as much organic carbon than conifers of AYC up to 06 (scenario 1), 12 (scenario 2: AYC 08 to12), 16 (scenario 3: AYC 14 to 16) respectively. The total organic carbon stock (tree, litter and soil) of the conifer plantations was estimated and the consequences of the landuse changes (three scenarios to replace the selected part of the conifer plantation) in accordance to the organic carbon model were also estimated.

A macro-language-based GIS model is proposed as an effective tool to show how climate change scenarios of UKCIP 1998 will be adopted as a decisive factor in forest management, such as replacing exotic conifers with native broadleaved woodland. Suitable sites for potential native broadleaved woodland (PNBW) for the future (2080) considering climate change scenarios were sketched and located by overlaying Mulligan's (1999) maps with the sites of the scenarios presented in the organic carbon model. Total organic carbon stocks which would be sequestered with these sites were also estimated.

The themes of the study, *i.e.* using GIS in week-by-week activities of forest management regional planning, may be transferable with the generic version of the models, particularly with macro language. A hypothetical study was presented to show the possible applications of these stated models in Bangladesh

All the models were generated with the macro language of the IDRISI GIS which can cope with any change by updating the spatial datasets and running the model within GIS for the week-by-week scenarios. This accommodative ability of models enables the manager to have an easy understanding and shows the scenario to the policy maker within short notice.

In conclusion, it was suggested that spatial data sets and GIS might contribute significantly in forest management, furthermore accommodating week-by-week activities into the database to derive regional forest ecosystem management decisions.

CHAPTER ONE
GENERAL INTRODUCTION

1.1 Background

The best future management of a forest is difficult to foresee, as the biological, economical, technological and political parameters are themselves difficult to predict (Holmgren, 1995). The challenge for a forest manager is to achieve a balance between nature and the demands of people, while considering global warming, justifying carbon for sequestration and eventually, revenue output. Along with these, one should also consider the global agreements on climate change, carbon sequestration and forest contribution in Agenda 21 of the United Nations Conference on Environment and Development (UNCED) in Rio de Jeneiro, 1992. These dictate a way to manage forest resources to overcome the stated parameters and act as the main impulse of the present study.

The outlines of future forest management were indicated by various scientists: Armstrong (1999) where management would be a healthy ecosystem; Lindenmayer (1999) who illustrated forest management as an enhanced biodiversity conservation; Landsberg and Gower (1997) concluded that carbon valuation would be the central point of forest management; Shvidenko *et al.,* (1997) described carbon as the most justified criterion for future forest management; Cairns and Meganck (1994) described the links between carbon sequestration, biological diversity and sustainable development. Kapos and Ireminger (1998) stated that forests are the repositories of much of the world's biodiversity, and therefore foresters must assume a degree of responsibility for their management and conservation. This should be done through a global, national and regional conservation priority setting with an understanding of the distribution of species and ecosystems.

Chapter 15 of Agenda 21, from the Rio conference (UNCED, 1992) also demanded a concrete effort on the part of national governments and international bodies to control the global forest cover and diversity. All these measures should be taken under the umbrella of the Intergovernmental Panel on Climate Change (IPCC, 1996) simulated global climate change scenario stating the equilibrium response of global surface temperature to a doubling of equivalent carbon dioxide concentration (the climate sensitivity) estimated in 1990 to be in the range 1.5^0C to 4.5^0C, with a best estimate of 2.5^0C.

Therefore, future sustainable integrated forest management requires combined scenarios which meet the local problems and prospects of forest resources and suitable for future climatic change perspective. It is clear that forest managers have to look ahead in diverse situations where data sets are required for climate change and related organic carbon estimation procedures. Many types of data are used simultaneously for the management of forests. Moreover, forest management requires a national policy for development of the sector within the view of regional interpretation and above all, under the concept of international conventions for forest management. These analyses should always be in a time frame and the prescriptions can also be changed as the situation demands. The prediction level should be high with the help of current, correct and appropriate data sets. This situation leads to potential use of the geographical information systems (*systems for capturing, storing, checking, manipulating, analysing and displaying data which are spatially referenced to the earth,* Burrough and McDonnell, 1998) to manage the spatial data-sets to integrate all stated data sources in a platform to provide management decisions through simulation modelling; otherwise it would be incredibly laborious. The application of geographical information systems (GIS) in forest management has been supported by various researchers (Barrett, 1997; Brown *et al.*, 1998; Dean, 1997; Kukreti, 1996; Smith *et al.*, 1995; Wilkinson, 1995; Treweek and Veitch, 1996; Mulder, 1993; Bateman and Lovett, 1998; Eliasson, 1991; Williams 1992; Grove and Hohmann, 1992; Menon and Bawa, 1997).

It can be revealed from the discussion that a need may exist to develop a theoretical framework and methodology for application of natural resource spatial data base in a GIS frame in order to formulate forest management strategies and to examine them with case studies.

1.2 Objectives

The objectives of the study are the following:

- to analyse the contribution that spatial data and geographical information systems (GIS) can make to strategic forest management at a regional planning level;
- to develop a GIS procedure to select potential areas for replacing conifer plantations with native broad leaved woodland;
- to examine the integration of spatial datasets and techniques within GIS as an example in windthrow management and native woodland expansion;
- to make a specific study of the role of GIS in modelling and estimating carbon sequestration in a change from exotic conifers to native broadleaved woodland;
- to make a specific study of the use of GIS incorporating climate change scenarios for analysing and predicting effects of native broadleaved woodlands on a regional scale;
- to recommend how methodologies developed using spatial data for the Snowdonia National Park (SNP) may be transferred to Bangladesh.

1.3 Justification

The management of all natural resources must now meet global, national, regional and local targets and guidelines. For this to be achieved in a co-ordinated, timely and effective manner, policy makers, managers, ecologists, economists and field staff must have access to both spatial and attribute data. The techniques for combining, managing and modelling such data have been developed in geographical information systems (GIS).

Land use managers must be aware of, and be able to predict, the impact that their actions may have on other land resources. Forest managers must themselves consider, agriculture, hydrology, wildlife, flora and fauna, human habitation and recreation among others. The last two decades have seen an increase in the collection, assembly and dissemination of spatial data never before experienced in the history of the earth. What might not have been foreseen was that forest managers would be required to make use of these data sets in their local planning and operational work on a week-by-week basis. This study will examine the modelling and application of natural resource spatial data as applied to several topical issues in forest management: windthrow, carbon sequestration and climate change.

1.4 Approach of the study

The following figures illustrate the approach of the present study:

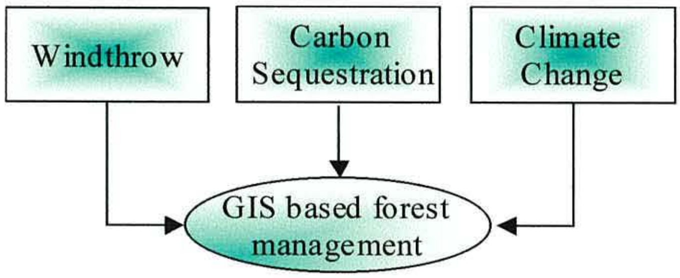


Figure 1.1 Study concept in application of the spatial data in forest management.

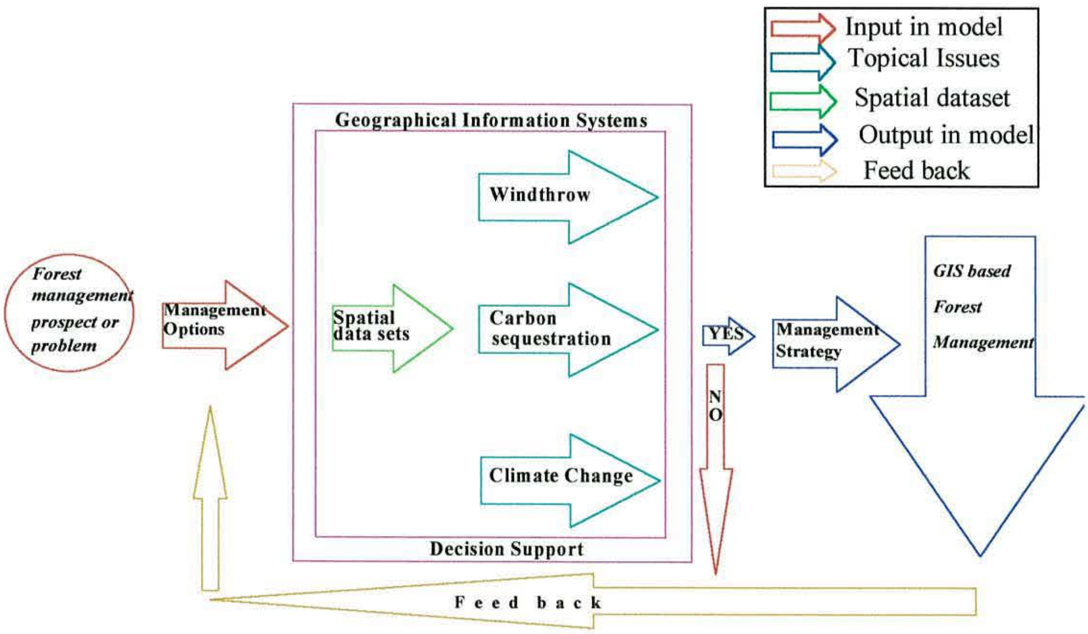


Figure 1.2 Schematic view of the application of spatial data within a GIS frame in forest management planning.

CHAPTER TWO
WINDTHROW

2.1 Windthrow: A topical issue for forest management

The objective of the study was to develop a methodology to analyse the integration of spatial data and techniques within geographical information systems (GIS) in strategic forest management at a regional planning scale with a forest management topical issue – windthrow. To fulfil the main objective, the following specific objectives were set:

- to quantify the patch shape, root penetration ability in soil and leaf presence in the endemic wind flow season (winter), in a forest area using GIS;
- to combine the contributions of all the stated factors with the windiness scale (**D**etailed **A**spect **M**ethod of **S**coring) prescribed by the Forestry Commission of Great Britain using GIS;
- to develop a new wind composite model (WCM) for species / site suitability;
- to develop a GIS procedure to run the model for a species in the study area, where wind is a problem for exotic timber plantations and where there is encouragement for the development of native woodland.

2.1.1 Background and rationale of study

Increasing attention has been paid to the role of disturbance, both minor and catastrophic, in determining ecosystem structure, species diversity and relative abundance of species (Bellingham *et al.,* 1992; Quine *et al.*, 1999). Several researchers (Bauer, 1964; Dittus, 1985; Bellingham, 1991; Webb, 1958; Foster, 1988b; Moore, 1988; Canham and Loucks, 1984) have explored windthrow as a topical issue in forest management. Wind damage is a serious threat to managed forests because it results in loss of timber yield, landscape quality and wildlife habitat (Quine *et al.,* 1995). Discussions of wind hazard have largely focused on mature stands confronted by catastrophic wind events (Ruel, 1995). However, windthrow by endemic winds is identified as a serious setback in UK forestry (Quine and Gardiner, 1992; Quine, 1994; Quine and White, 1993; Quine and Bell, 1998). Reducing windthrow and its risk management have become forest management issues in many parts of the world (Ruel, 1995). This situation demands a good understanding of wind disturbance and recovery of forest cover.

Wind may actually contribute to forest management if the resulting 'gaps' and windthrow provide regeneration opportunities for native species. Fries *et al.* (1997) and Quine *et al.* (1999) suggested that if forest management strategies mimic natural processes, blend natural structures and include natural composition into the production forest, it could lead to improved management systems.

The threat of windthrow has been an important influence on the management of Britain's upland forest (Quine, 1994). Geographical information systems (GIS) may be a useful tool to integrate the spatial data sets of related factors with wind dynamics. Considering this view, Figure 2.1.1 illustrates how the main objective of the study will unfold considering windthrow as a management issue:

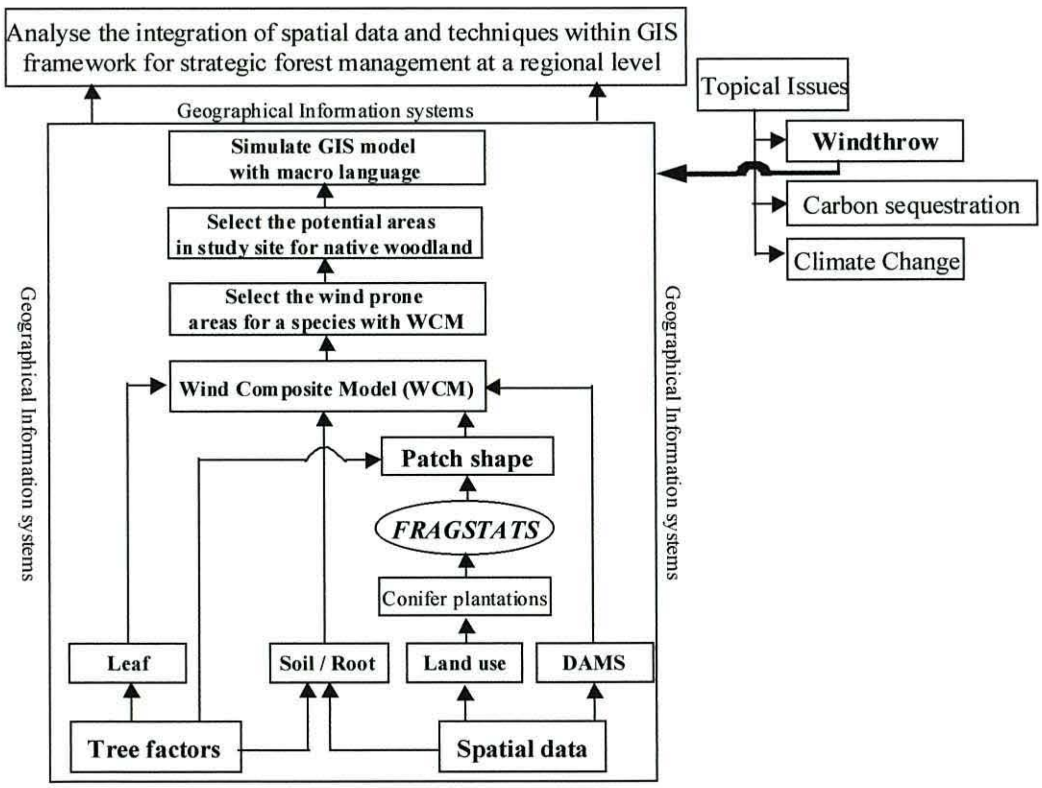


Figure 2.1.1 Illustrates the flow of specific objectives towards the main objective.

The Forestry Commission of Great Britain studied wind dynamics and prescribed a scale of windiness called **D**etailed **A**spect **M**ethod of **S**coring (DAMS) (Quine and White, 1993). DAMS combines the wind zones of Great Britain, elevation, topex and aspect with its funnelling effect. DAMS is preferred and most applicable for field surveys in complex terrain (Quine and White, 1993). The main aim of DAMS is to set the windthrow hazard classes for indicating which forest stands are in danger to the forest managers.

2.1.2 Developing the wind composite model

However, the question remains, is DAMS an appropriate yardstick for an existing forest? How does a forest manager take a decision with DAMS for a forest patch? If any patch is changed in a forest then obviously the windiness pattern also changes, with that situation is there any chance to change the value of DAMS to predict a future course of action? These questions indicate that there exists a need to develop a theoretical framework and a model, and forest managers would be required to make use of these data sets in their local planning and operational work on a week-by-week basis. It eventually provides a scope to utilise the national level data sets at regional level planning using GIS.

DAMS didn't incorporate tree-related factors such as patch shape, leaf presence in winter and the soil class in relation to root penetration. These factors can potentially influence how much force will be required to overthrow a tree. If these factors are also combined with DAMS, then it might act as a management tool for forest reconstruction and planning. Geographical information system (GIS) can play a vital role and act as a platform on which tree factors and soil classes can be combined simultaneously with DAMS, from national to local scales, helping to prescribe strategies for forest managers.

This study will propose a model to accommodate tree and soil factors with DAMS using the IDRISI GIS. The model will eventually derive a new model named **w**ind **c**omposite **m**odel (WCM) which combines DAMS with the patch shape, soil classes and leaf presence in winter.

WCM will demonstrate the species/site relationship with windiness for different species to a forest area (Figure 2.1.2).

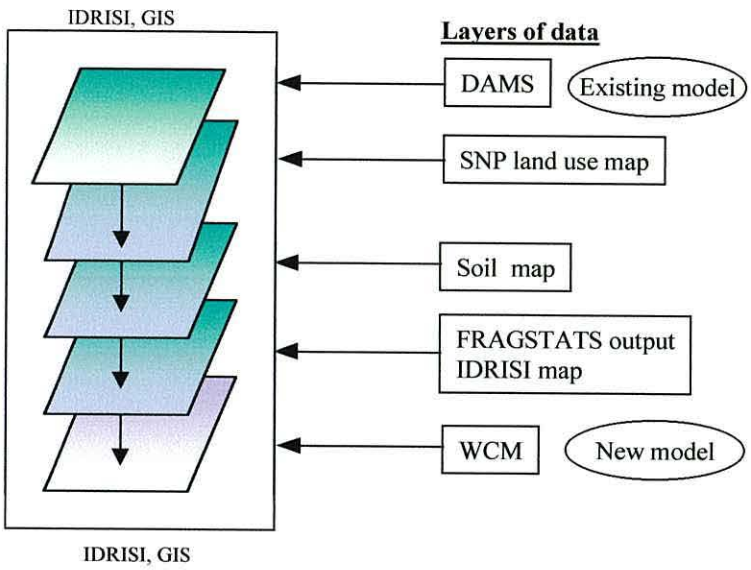


Figure 2.1.2 Application of GIS in collecting, storing, retrieving at will, transforming and displaying spatial data in the case study area to produce the wind composite model.

The Snowdonia National Park (SNP) is an area in which windthrow is a problem in forests. Furthermore, the Snowdonia National Park Authority (SNPA) is trying to encourage the development of native woodland (SNPA, 1995). The WCM is applied in the Snowdonia National Park as a case study site and using *Picea sitchensis* (Sitka spruce) as a sample species. This species comprises 95% of the total conifer plantation of the study area. Four scenarios of WCM combine the contribution of patch shape, soil class and leaf presence with DAMS. The areas which are *too windy* may be unsuitable for commercial plantations of the target species (*Picea sitchensis*), are located in maps using GIS. The total procedure is carried out with the IDRISI GIS, demonstrating the contribution of spatial data sets in forest management planning using GIS.

2.2 Literature review

2.2.1 Windthrow as a forest management issue

Wind is a major cause of damage in the forestry sector (Mitchell, 1995; Williams and Douglas, 1995; Evans and Paterson, 1990; Wright and Quine, 1993; Miller *et al.,* 1987) and is a major natural disturbance agent (Mitchell, 1998; Williams and Douglas, 1995; Foster, 1988a; Coates and Burton, 1997; Ratcliffe and Peterken, 1995). Furthermore, windthrow is a risk (Peltola, 1996; Somerville, 1980) and treated as a threat to forest management (Quine and Gardiner, 1992; Quine and White, 1993; Quine and Bell, 1998). It provides opportunities for pathogens, unnecessary fuel loading; salvage is dangerous and costly (Mitchell, 1995). Windthrow is a hazard (Mitchell, 1998; Quine and Wright, 1993) and also limits the mobility of wildlife and recreationists (Mitchell, 1995; Quine *et al.,* 1995). Windthrow is a forest management issue in many parts of the world (Ruel, 1995; Ruel *et al.,* 1998, Gallagher, 1974). In terms of management of forests, windthrow disrupts silvicultural management (Gallagher, 1974) and also interrupts integrated forest management systems (Mitchell, 1998; Quine *et al.,* 1995). In upland conifer forests subject to high risk of premature windthrow, an important management objective is to achieve the maximum timber values (Hart, 1994). Gardiner and Quine (2000) developed a conceptual model for abiotic risk management with an emphasis on wind damage. They suggested that mathematical models provide an opportunity to calculate the risks of forest. Above all, the impacts of windthrow are generally negative regarding stand or forest level management objectives (Mitchell, 1998; Quine *et al.,* 1995).

2.2.2 Factors responsible for windthrow

Various studies have been carried out about windthrow and its dynamics. Mitchell (1995) indicated that three factors are responsible for windthrow: topographic exposure, soil properties and stand characteristics. However, Mitchell (1998) and Quine (1994) add another cause *i.e.* stand treatment, which includes harvesting pattern, choice of afforestation site, thinning practices and felling age. In addition, studies on windiness have indicated that this depends on: wind zone, elevation, topex and aspect (Quine and Bell, 1994; Bell *et al.,* 1995; Hale *et al.,* 1998). Studies on critical wind speed, at which the wind force acting on the crowns of individual trees is sufficient to cause bole or root failure, were conducted (Mitchell, 1995; Smith *et al.,* 1987). The factors involved to snap a tree by wind are tree height, crown size and density, stem thickness, wood strength, wood elasticity, root-soil mass, root strength and soil shear strength (Mitchell, 1995). Another study suggested that wider spacing and heavy thinning reduced risk of wind damage (Munishi and Chamshama, 1994). Quine and Gardiner (1992) showed critical height and wind hazard class relationship in manipulating the stand structure. Gallagher (1974) concluded the factors responsible for windthrow were climate, site and the existing silvicultural practices, specially thinning and species compositions. MacKenzie (1976) considered six factors to be responsible and suggested they should be weighted to assess the windthrow risks. They were soil type, angle of slope, aspect, altitude, exposure and geology. Ruel (2000) suggested critical factors for windthrow were wind direction, exposure, stand treatment at local and regional scale, stem defects on individual trees with wind speed, species, age, soil characteristics and silvicultural operations.

2.2.3 Wind hazards

Financial losses due to windthrow (without catastrophic wind blow) have been described as ranging from 2.5% to 15% of the total revenue earned {Mitchell, 1995 (4%); Mergen, 1954 (2.5%); Quine and Bell, 1994 (15% in Britain)}. Windthrow due to catastrophic storm is particularly hazardous (Herbert *et al.,* 1999; Lugo *et al.,* 1983; Webb, 1958; Mason and Quine, 1995; Reilly, 1991). A number of scientists (Bellingham *et al.,* 1995; Brokaw and Walker, 1991; Emanuel, 1987; Gray, 1990; Kapos *et al.*, 1991) have studied the effects and frequency of catastrophic wind events on forest vegetation. The return time (Bellingham, 1991; Everham III, 1996) and recovery (Foster and Boose, 1995; Tanner *et al.,* 1991, Whigham *et al.,* 1991; You and Petty, 1991) have also been studied.

The British Isles has one of the windiest climates in the world. Here winter gales, with mean hourly wind speeds of *c*.20 ms^{-1} gusting up to *c*.30 ms^{-1} have been recorded (Deans and Ford, 1983). Quine and Bell (1998) presented the results of monitoring windthrow occurrence (over 4842 ha of study area wind thrown area was 37560 m^2 in 1998, 1694100 m^2 in 1994) in eight forest areas in Britain. The results also showed the frequency and increment rates of windthrow events were higher in the northern and western zones than those recorded as wind-prone forests. Gallagher (1974) shows records of windthrow in Table 2.2.1.

Table 2.2.1 Windthrow in forests of the Republic of Ireland (Gallagher, 1974).

Year	Forests damage hectares (in thousand)	Highest Gust ($m\ sec^{-1}$)	Mean wind speed ($m\ sec^{-1}$)	Year	Forests damage hectares (in thousand)	Highest Gust ($m\ sec^{-1}$)	Mean wind Speed ($m\ sec^{-1}$)
1950	22 (5.9)	37.008	24.158	1963	32 (65.5)	38.550	27.242
1951	35 (3.4)	42.148	26.214	1964	11 (58.0)	38.550	26.214
1952	81 (113)	34.952	20.560	1965	11 (32.7)	45.232	30.840
1953	02	35.466	17.990	1966	13 (37.7)	44.718	29.812
1954	-	42.662	20.560	1967	06 (19.6)	40.092	29.812
1955	02 (126.5)	35.466	22.616	1968	02 (2.7)	46.774	30.840
1956	04 (4.7)	41.634	20.560	1969	-- (4.3)	36.494	23.644
1957	144 (281.5)	48.316	33.924	1970	-- (2.3)	36.494	22.616
1958	21 (3.5)	44.204	26.728	1971	68 (2.6)	39.064	23.130
1959	19 (1.5)	43.690	27.242	1972	39 (3.0)	41.634	28.784
1960	26 (40.5)	39.064	14.906	1973	65 (21.0)	-	-
1961	34 (25.1)	50.372	33.924	1974	150	35.980	48.316
1962	140 (213.0)	41.120	27.756	**Wind and gust speed expressed in $m\ sec^{-1}$ (updated from knots)**			

2.2.4 Wind and stand dynamics

Hart (1994) discussed wind dynamics and illustrated that wind behaviour was dependent upon geographical position, topography, altitude, aspect, and degree of slope as well as the structure of the stand both inside and on its periphery. Somerville (1980) illustrated wind dynamics to discuss the phenomenon of windthrow.

The following diagram shows energy gain and loss for a tree under wind stress in that study:

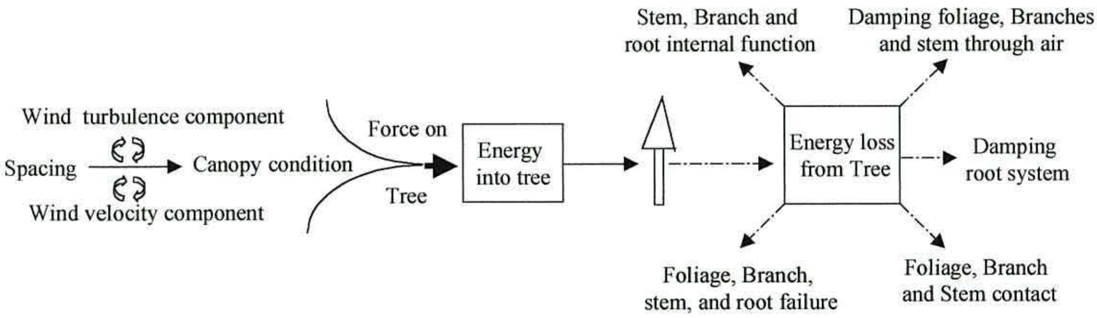


Figure 2.2.1 Process of energy gain and loss for a tree under wind stress (Somerville, 1980).

Valinger (1992) presented the growth patterns of stem and crown formation of Scots pine (*Pinus sylvestris*) and reported that wind has significant influence on the growth of the stated species. Windthrow also plays a major role in stand and soil dynamics (Ruel, 1995). It is evident that windthrow affords easier growth of shade tolerant species and speeds up its development; it also favours intolerant or intermediate species (Brown, 1977; Ruel *et al.,* 1998). Windthrow mixes the mineral and organic layers creating favourable seed beds (Ruel, 1995) which support the dynamics of recovery illustrated by Evans and Paterson (1990).

2.2.5 Assessment of windthrow hazard

MacKenzie (1976) classified windthrow risk into four classes. The classes had a score from below 10 to over 20 (very high risk: for sites with a total score of 20 or more points; high risk: 16 to 19 points; moderate risk: 11 to 15 points; and low risk: for those sites scoring 10 points or less).

Mitchell (1995) presented windthrow hazard evaluation with respect to topographic exposure, stand characteristics and soil properties. He classified windthrow hazard as low, moderate and high. However, Mitchell (1998) revised his assessment procedure and termed windthrow risk as a combined effect of biophysical hazard (environmental factors) and treatment risk (management factors). The study presented the following framework in order to assess windthrow:

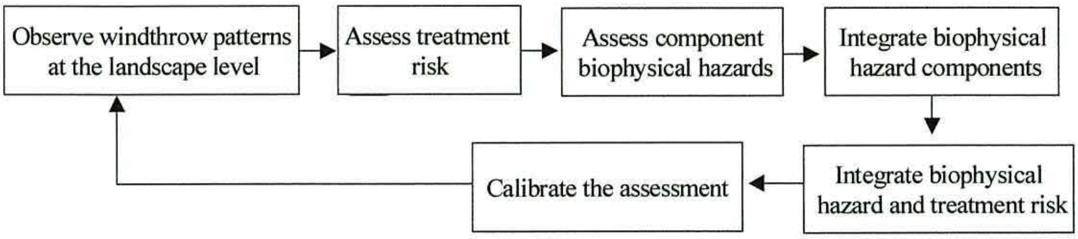


Figure 2.2.2 Framework for assessing windthrow (Mitchell, 1998).

Miller *et al.* (1987) assessed the wind exposure for upland Britain and divided Britain into seven wind zones in the following way:

Figure 2.2.3 Seven wind zones (A to E) based in the British Isles (Adapted from Miller *et al.*, 1987).

Miller *et al.* (1987) also presented the following description of the **top**ographic **ex**posure (topex) method.

"An optical clinometer and a sighting compass are used to measure the angles of elevation to the visible skyline at the eight major points of the compass. The sum of the eight skyline angles constitutes the topex value for the assessment location, and topographic shelter is defined on a non-linear scale, with subdivision of five exposed zones." Another way to assess the exposure classification derived from flag attrition (tatter) rates was expressed in the following way: *"the process consists of a series of fine unhemmed Madapollam cotton flags (380mm x 305mm) on vertical mounts, 1.5m above the ground (Reynard and Low, 1984). As with topex assessments, it is important to cover the full range of elevation and aspect changes present on the site in order to obtain reliable data. Flags are changed and assessed every two months throughout the year for a three-year period, thereby smoothing out any annual aberrations in the exposure level of the site. Exposure is expressed as the average loss of surface area of the flag in square centimetres per day (cm^2 day^{-1}), calculated over the total assessment period"*

Table2.2.2 Exposure classification by the topex method (Miller *et al.*, 1987).

Range of topex values (Total of eight skyline elevation angles)	Relative exposure zone
0 – 10	Severely exposed
11 – 30	Very exposed
31 – 60	Moderately exposed
61 – 100	Moderately sheltered
101 +	Very sheltered

The relations between attrition (tatter) rates and exposure classes are as follows:

Table 2.2.3 Exposure classification derived from flag attrition rates (Miller *et al.*, 1987).

Mean loss of flag area (cm^2 day^{-1})	Relative exposure zone
> 13.0	Severely exposed
10.1 - 13.0	Very exposed
6.6 - 10.0	Moderately exposed
4.0 - 6.5	Moderately sheltered
< 4.0	Very sheltered

2.2.5.1 SAMS and DAMS

Quine and White (1993) revised the windiness scores of Miller *et al.* (1987) for windthrow hazard classification. Wind zone, elevation and total topex scores were revised and an aspect score was introduced. The revised windiness scores could be derived in two ways: selection of a single aspect example: SW, NE {the Single Aspect Method of Scoring (SAMS)} or by calculation from topex sector values {the Detailed Aspect Method of Scoring (DAMS)}. The study produced a new revised wind zone score of -7 to +6. The revised wind zone for Great Britain is the following:

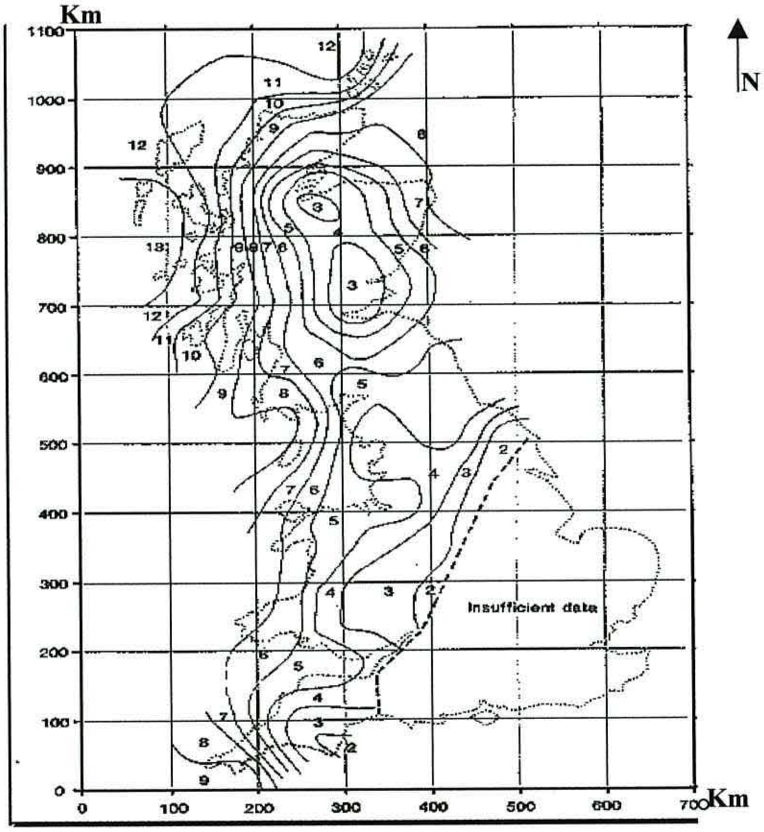


Figure 2.2.4 Revised wind zone map of Great Britain providing wind zone scores at intervals of one unit (Adapted from Quine and White, 1993).

Both elevation and the topex score obtained from map or altimeter readings and from site, respectively, were converted into a score with the help of prescribed regression lines depending on the choice of aspect scoring method (SAMS or DAMS). The aspect scores were ascribed according to the following tables:

Table 2.2.4 Aspect scores for the Single Aspect Method of Scoring (SAMS). (Adapted from Quine and White, 1993)

Aspect	**ALL**	**NIL**	**N**	**NE**	**E**	**SE**	**S**	**SW**	**W**	**NW**
Hazard score class	+1.0	-1.0	0	-0.5	-0.5	0	0	+0.5	+1.0	0

Note: An aspect of ALL applies to level or gently sloping sites that have no single or defined aspect but are well exposed, *e.g.* hilltop or plateau. An aspect of NIL applies to level or gently sloping sites that have no single or defined aspect but are sheltered, such as valley or basin.

2.2.5.2 Aspect scores for the Detailed Aspect Method of Scoring (DAMS).

Aspect effect

Table 2.2.5 Aspect scores for the Detailed Aspect Method of Scoring (DAMS). (Adapted from Quine and White, 1993)

Aspect	N	NE	E	SE	S	SW	W	NW
Hazard score class	+49	-19	-17	+48	+27	-63	-59	+34

Note: Multiply each topex sector value by the appropriate constant. Add the results and divide by 1000. The resulting score may be positive or negative and is added to or subtracted from the other windiness score accordingly.

Funnelling effect

$$\text{Funnelling effect} = 0.01074 \times \sqrt{\left(\underset{\text{Sector Value}}{\text{N}} - \underset{\text{Sector Value}}{\text{E}} + \underset{\text{Sector Value}}{\text{S}} - \underset{\text{Sector Value}}{\text{W}}\right)^2 + \left(\underset{\text{Sector Value}}{\text{NE}} - \underset{\text{Sector Value}}{\text{SE}} + \underset{\text{Sector Value}}{\text{SW}} - \underset{\text{Sector Value}}{\text{NW}}\right)^2}$$

Note: Enter the appropriate topex sector values into the equation. The value is always positive.

2.2.6 Diversity and windthrow

Either through windthrow or wind damage, recruitment of woody species after a windthrow event appears to be sufficient to maintain forest structure, but composition may be altered (Williams and Douglas, 1995; Fensham and Bowman, 1992; Nachtergale *et al.*, 1997). Evans and Paterson (1990) illustrated that when wind damage has coincided with a good seed year for many broad-leaved species and Scots pine (*P. sylvestris*), rapid colonisation may often occur where bare ground has been exposed and recommend that the duty of forest managers is to identify individual trees of suitable species early and protect them from competition and damage.

2.2.7 Patch shape, crown and windthrow

Mergen (1954) illustrated the relationships between crown and root balls in regard to wind. MacKenzie (1976) reported that rooting and crown characteristics had an important effect on windthrow. The study also illustrated that on high and very high risk sites only species having a good tolerance of anaerobic soil conditions, an ability to develop wide, strong root plates, or crown characteristics that reduce wind resistance were suitable. However, it didn't weight rooting ability and crown characteristics in windthrow risk assessment scoring. Robertson (1987) illustrated the uses of a tree crown as an indicator of the wind speed it resisted. He graded trees in two systems: 1) Griggs-Putnam index for conifers and 2) Barsch index for broadleaves and also indicated that it was much more difficult to use for stands of trees than for a single tree for a wind flow study. Eysenrode *et al.* (1998) studied the gap shape. They quantified gap shape from aerial photography, with the ratio of gap area and gap perimeter based on referential geometrical figures, such as circle, square, rectangle, ellipse, and isosceles and equilateral triangle. Oliver and Mayhead (1974) illustrated the potential role of the canopy with gales and gusts and mentioned that friction velocity and height of the tree canopy are the major factors to restrict the velocity of endemic wind in a forest with tree cover. They also presented a generalised summary of theoretical wind profile above and below the top of the canopy and showed that above the canopy level the velocity of the wind is much more than below the canopy base. It defends crown as a major factor for wind dynamics in the forest crop. Oliver and Mayhead (1974) calculated wind speed within the tree canopy as: $u_Z = u_h [1 + \alpha (1- z / h)]^{-2}$, where u_Z is the wind speed at height z, u_h is the wind speed at the top of the canopy and α is the leaf attenuation coefficient, which they found to equal 2.5.

Oliver and Mayhead (1974) calculated wind speed over the canopy as follows:

$$u_z = (u_* / k) \log_e\{ (z-d) / z_o \}$$

Where u_z is the wind speed (m/sec) at height z (m), d is zero plane displacement (m), z_o is roughness length (m), k is universal (von Karman) constant = 0.41, and u_* is friction velocity (m/sec).

It is revealed from the study of Smith *et al.* (1987) that the density and distribution of foliage determine the wind speed profile within a forest and reported the following table where the ratio of average wind speed within the stand (U_c) to the wind speed at the crown top (U_h) is summarised:

Table 2.2.6 Ratio of average wind speed within the stand (U_c) to the wind speed at the crown top (U_h). (Adapted from Smith *et al.*, 1987)

Species	Stand description	Data source	$U_c : U_h$
Sitka spruce	34.5 ft tall, dense	Shaw 1977	0.16
Scots pine	50.9 ft tall, open	Shaw 1977	0.24
Ponderosa pine	70.0 ft tall, open	Shaw 1977	0.34
Japanese larch	34.1 ft tall, open	Shaw 1977	0.36
Black spruce	11.5 ft tall, open	Berglund and Barney 1977	0.63
Lodgepole pine	10.0 m tall, 2 x 2 m spacing	Bergen 1971	0.5
White and red pine	10.5 m tall, 1.2 x 1.5 m spacing	Raynor 1971	0.22
Conifer	90 ft tall, dense with dense understory	Reifsneider 1955	0.50
Hardwood	60 ft tall, dense with dense understory	Reifsneider 1955	0.66
Conifer	70 ft tall moderately dense without understory	Fons 1940	0.33
Stika spruce	10.5 m tall, dense	Landesberg and James 1971	0.25
Black spruce	8.8 m tall, dense	Brown 1972	0.13

Smith *et al.* (1987) concluded that the crown contributed much more than the stem to drag and much more than the stem to the turning moment acting at the base. Petty and Swain (1985) considered both the variation of wind speed within the canopy and the vertical distribution of the weight of the crown. Patch canopy arrangements had significant effects on wind flow. This was especially the case when the density of the surrounding canopy was reduced, thereby increasing overall wind speeds in and near clearings (Miller *et al.*, 1991). Cameron and Dunham (1999) suggested that trees that either overturn or snap were bending more than undamaged trees (because of their low modulus of elasticity), thereby introducing a greater component of crown weight to the overall forces acting on the stem: this may be associated with compression wood. A simple subjective system of crown classification developed by Dawkins (1958) which was found to be reliable, gave consistent results and correlates well with increment and subsequent mortality (Wyatt-Smith and Vincent, 1962; Alder and Synnott, 1992). Exposed crown radius measurement was done by Cole (1995). Skatter and Kucera (2000) suggested that crown asymmetry might be a major reason for tree breakage by wind action.

Quine and Bell (1998) used the shape index (the fractal dimension) to measure gap shape due to windthrow. The results revealed that the gap size distribution remained highly skewed with predominance of small gaps, despite an increase in numbers across all gap size classes and an increase of maximum gap size.

Zhu *et al.* (2000) examined the influence of crown shape on wind speed and suggested that there is a consistent relationship between wind speed and crown thickness. The results of the study also showed that wind speed in the lower region of the crown where the shape was spherical was lowest, and it increased as the crown shape tended to an elongated shape. Dunham and Cameron (2000) suggested that crown shape had an effect on the wind damage and specially small crown of trees might be more susceptible for the windthrow.

2.2.8 Soil and root contribution to windthrow

Any species of conifer, whose main root-mass remains within 30 cm of the surface, whether on deep or shallow peat soil, would be susceptible to wind-throw (Carey and Barry, 1975). Waldron and Dakessian (1981) examined the strength of the soil-root bond from purely frictional considerations and revealed that the limitation of the soil-root bond was imposed by the soil rather than by plant species, root morphology, or root strength. Furthermore, Mason and Quine (1995) pointed out that the main limiting factor to tree growth is wind disturbance, compounded by shallow rooting on gleyed soils. Several researchers (Biddle 1998; Busgen and Munch, 1929; Helliwell, 1986; Coutts, 1983; Helliwell, 1989; Helliwell and Fordham, 1992) have described the structures and development of roots. They discussed different shapes, forms and types of roots, root: shoot ratio and their anchorage properties of the soil. Hart (1994) revealed that rooting of trees had often been restricted to the top 25-45 cm of soils by water logging and anchorage of trees had often proved inadequate in strong winds. Root morphology was strongly affected by soil type, with the depth and strength of roots being influenced by soil moisture and aeration, and by physical conditions within the soil profile. The physical condition of the soil played a large part in the root development of individual trees, and that relatively small increases in rooting depth could produce considerable increases in tree resistance, sufficient in many cases to prevent windthrow (Fraser, 1960). Cutler *et al.* (1989) carried out a detailed study of windblown tree roots (the 1987 storm in the UK). According to this study the incidences of windthrow on various subsoil types were as follows:

Table 2.2.7 Incidences of windthrow on various subsoil types (Cutler *et al.,* 1989)

Name of species	Sand (%)	Clay (%)	Chalk (%)	Silt (%)	Peat (%)	Loam (%)	Gravel (%)	Mixed Sand & Silt (%)
Quercus	43.4	26.9	8.6	0.6	0.0	4.0	15.4	1.1
Fagus	33.6	32.0	19.7	0.8	0.0	8.2	5.7	0.0
Pinus	51.1	17.8	15.6	0.0	4.4	0.0	8.9	2.2
Tilia	40.0	24.0	12.0	0.0	2.0	0.0	22.0	0.0
Picea	55.6	42.2	0.0	0.0	0.0	0.0	0.0	2.2
Betula	57.9	13.2	2.6	0.0	0.0	7.9	7.9	10.5

Coutts (1983) considered the root architecture of Sitka spruce (*Picea sitchensis*), together with soil and root plate relationships and also calculated their tensile strength properties. Root structure and stability for Sitka spruce (*P. sitchensis*) was modelled by Deans and Ford (1983). The model simulated aspects of resistance to overturning which root systems offered when trees were swayed by the wind. Gasson and Cutler (1990) did the detailed studies about root plate morphology with windthrow trees of 1987 (UK). The relationship with soil classes with the same windthrow trees was examined by Cutler *et al.* (1990). Coutts (1986) stated that the main components responsible for root anchorage in relation to tree stability were soil resistance, windward roots, hinge and the weight of the root-soil plate. Puhe (1994) illustrated that the development of tree root was seriously hampered by its soil type (photo 2.2.1. and photo 2.2.2).

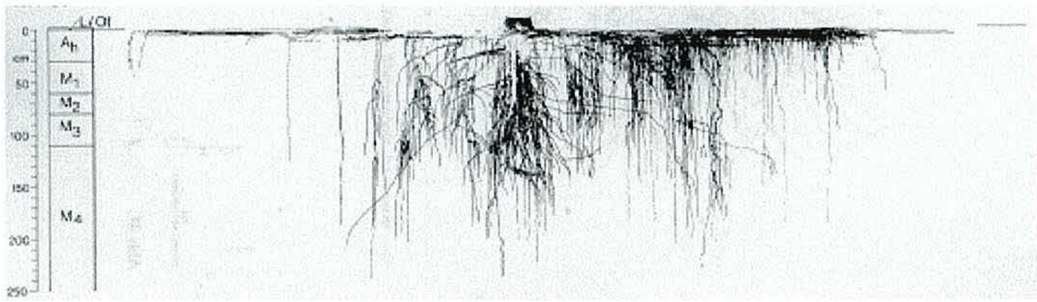


Photo 2.2.1 Root system of Sitka Spruce developed in normal soil (Puhe, 1994).

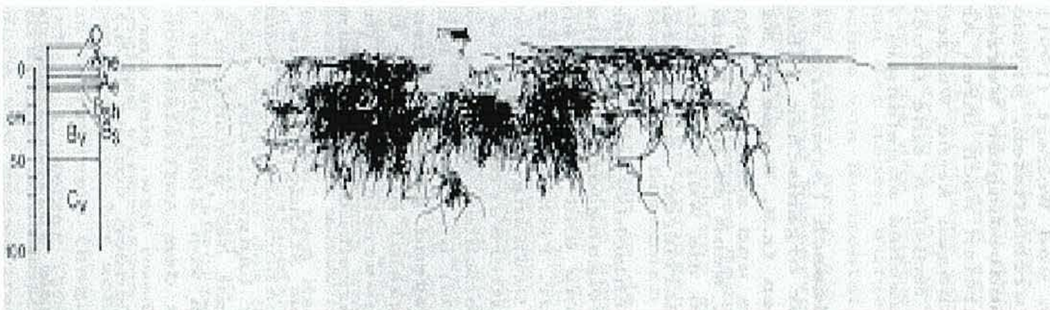


Photo 2.2.2 Root system of Sitka Spruce developed in acidic soil (Puhe, 1994).

2.2.9 Landscape contribution to windthrow

Any windthrow in the forest provides a gap in the stand. The gaps, which may be small or large, can have a very significant influence in the ecosystem. In unmanaged forests, naturally formed canopy gaps are crucial for the initiation of the regeneration cycle of most tree species (Coates and Burton, 1997; Healey, 1996). Studies of gap dynamics in order to understand the role of disturbances like windthrow in forest ecosystems are necessary for effective forest ecosystem management. Several scientists (Fries *et al.,* 1997; Orwig and Abrams, 1995;

Ratcliffe and Peterken, 1995; Timo and Pauli, 1998) worked on windthrow and gap formation, as well as their relationship with the biodiversity and the recovery of plant species (Coats and Burton, 1997; Foster, 1988a; Hodge *et al.*, 1998; Lindenmayer, 1999; Noss, 1999; Simberloff, 1999; Wadsworth and Treweek, 1999; Zhang *et al.*, 1999).

2.2.10 Fragmentation analysis

Application to windthrow

Fragmentation means the processes of geographical isolation. Gaps are small openings in forest cover caused by local events, particularly tree fall. Fragments due to gaps play a fundamental role in structuring forests and maintaining species diversity (Farina, 1998).

Farina (1998) explained that fragmentation was a scale-dependent process and had different spatial arrangements, causing different effects on other ecological processes. Fragmentation increases the vulnerability of patches to external disturbance, for instance wind or drought, with consequences for the survival of these patches and for supporting biodiversity (Nilsson and Grelsson, 1995).

FRAGSTATS

The unequal distribution of natural phenomena, such as underlying rock type geology, the distribution of rain across a mountain range, or the distribution of tree cover in catchments, creates complicated mosaics to which organisms react. To measure this complexity Euclidean geometry often seems inadequate and new approaches are required (Farina, 1998; Mandelbrot, 1982). ***FRAGSTATS***, a computer automated software, was developed to quantify landscape structure (Mcgarigal and Marks, 1995). Two separate versions of *FRAGSTATS* exist: one for vector images and another for raster images. The vector package is an Arc/info AML that accepts Arc/info polygon coverage. The raster version is a C programme that accepts ASCII image files, 8 or 16 bit binary image files, Arc/info SVS files, ERDAS image files and IDRISI image files. A part of matrices computed in FRAGSTATS are shown in Appendix 2.6.

2.2.11 Windthrow and GIS

Various researchers (Hale *et al.,* 1998; Nåsset, 1997; Quine, 1995; Wadsworth and Treweek, 1999) have applied geographical information systems (GIS) to assessing windthrow in their studies. Eastman (1997) applied the IDRISI GIS for hazard assessment. Quine and Wright (1993) used a digital terrain model (DTM) with the IDRISI GIS platform to find out the effects of revised windiness scores on the distribution of windthrow classes. Quine and White (1998) also applied a DTM using IDRISI to calculate the topex sector values for the prediction of distance limited site windiness. The IDRISI platform with its DTM module were also successfully used to calculate an improved windiness score for every quarter hectare of upland Britain (Quine and Bell, 1994; Bell *et al.,* 1995). Figure 2.2.5 illustrated the flow diagram of process of calculating windthrow hazard classes from digital terrain models (Bell *et al.*, 1995).

Payn *et al.* (1999) simulate a model using GIS incorporating soil and growth map and suggested that GIS can be used as a logical tool for analysis and presentation of trends. Again, Quine and Bell (1998) used standard modules of IDRISI GIS to compute the total study area, percentage of windthrown trees per area for each year and the perimeter of individual gaps.

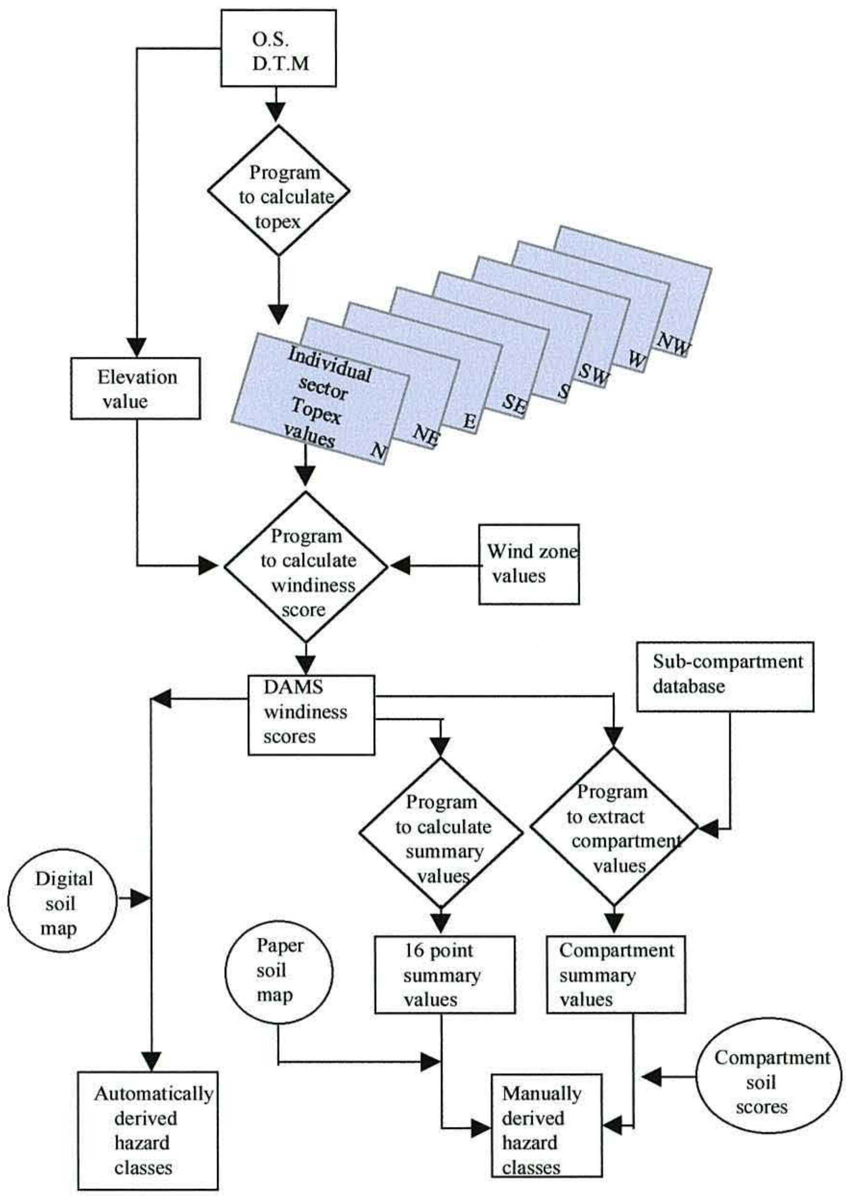


Figure 2.2.5 Flow diagram describing the process of calculating windthrow hazard classes from digital terrain models (Bell *et al.*, 1995)

2.3 Materials and Methods

2.3.1 Introduction

The Forestry Commission of Great Britain developed the **D**etailed **A**spect **M**ethod of **S**coring (DAMS) as a windiness scale with a view to indicate the scale of hazard it may accept. Using DAMS, the Forestry Commission predicted a suitability limit for the planting of species. Pyatt and Suarez (1997) in their technical paper illustrated the matter with respect to 25 major tree species in the United Kingdom. They indicated that all the species were suited to zones with DAMS scores 7 to 13. Then suitability became more specific from 13 to 22 (varies with species) and unsuitability commenced from 22 upwards for all the species listed including native woodland species (Appendix 2.4).

It is clear that the DAMS score for woodland can be used to estimate - how much forested land is under wind risk. Adding a soil score to the DAMS score indicates the hazard zones for the forest (Quine and Bell, 1994).

A forest area usually has some patches and every patch of trees makes a single 'virtual patch shape' (Figure: 2.3.1a) which may accelerate or retard or divert the wind velocity. It is wise to consider the shapes of patches with their respective soil types and combine this with windiness. This study will consider the shape of each patch in the forest, soil classes (suitability with respect to root penetration) and leaf existence in the season of strong endemic and catastrophic wind in Great Britain: winter. Quine (1994) illustrated the components of the vulnerability of a tree and categorised the above-mentioned factors as persistent, progressive and episodic respectively.

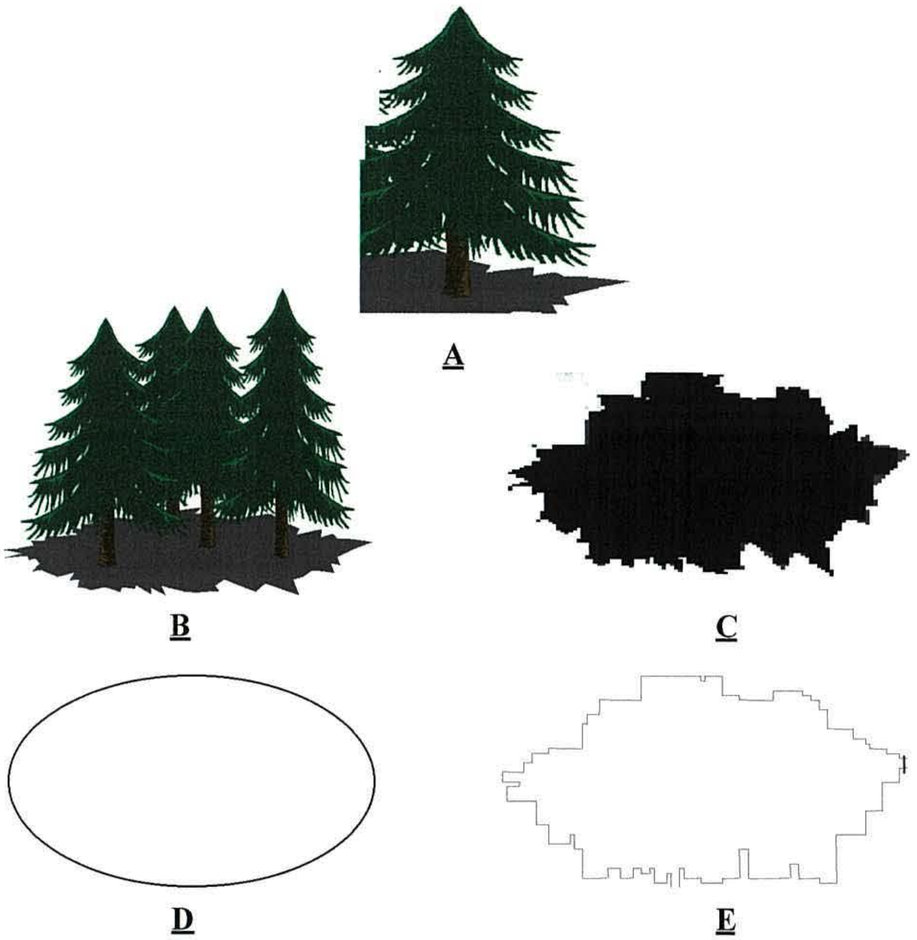


Figure 2.3.1a Illustrating:
A. side view of a single tree with its crown.
B. side view of a patch of trees.
C. aerial view of the virtual crown of a patch.
D. patch shape in Euclidean geometry.
E. patch shape **C** in GIS raster format

2.3.1.1 Model

The following is a model, has been developed illustratively to envisage the wind diversity with respect to species in a forest patch.

WCM = D_m [1+ $\sum T_i$]...(Model 1)

= D_m {1+ (RX + CY +Z)}...(Model 1a)

where, D_m = DAMS value, T_i = Tree factors, R = Root, X= Soil type,

C = Patch crown form, Y = Patch shape, Z = Leaf presence in winter.

WCM = **W**ind **c**omposite **m**odel

At this juncture, root parameters were constant with respect to the species because their development depends on the soil where it penetrates. Furthermore, patch crown form of each species is also constant for its phenology architecture. Patch shape and soil type varied with species and location. Therefore, if patch shape and soil type were combined with DAMS, in presence or absence of leaves in winter, this would indicate which areas are too windy for any particular species. Eventually, model 1 (stated above) stands in the following way:

WCM = D_m [1+ $\sum T_i$]... (Model 1)

= D_m { 1+ (aX + bY +cZ)}.................................... (Model 1b)

where, a, b, c = coefficients for proportionate contributions of factors.

The following flow diagram explains how the model for WCM was developed:

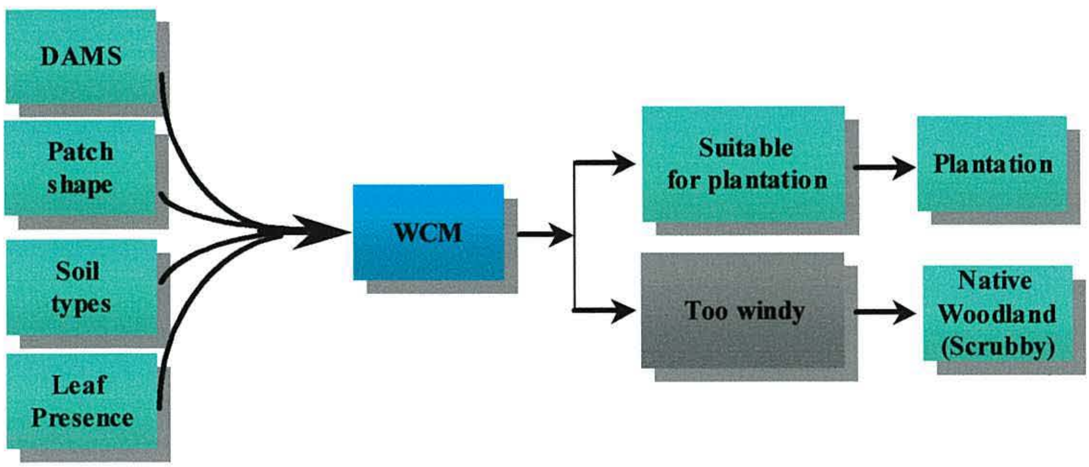


Figure 2.3.1 Flow diagram demonstrating the wind composite model (WCM) for any species.

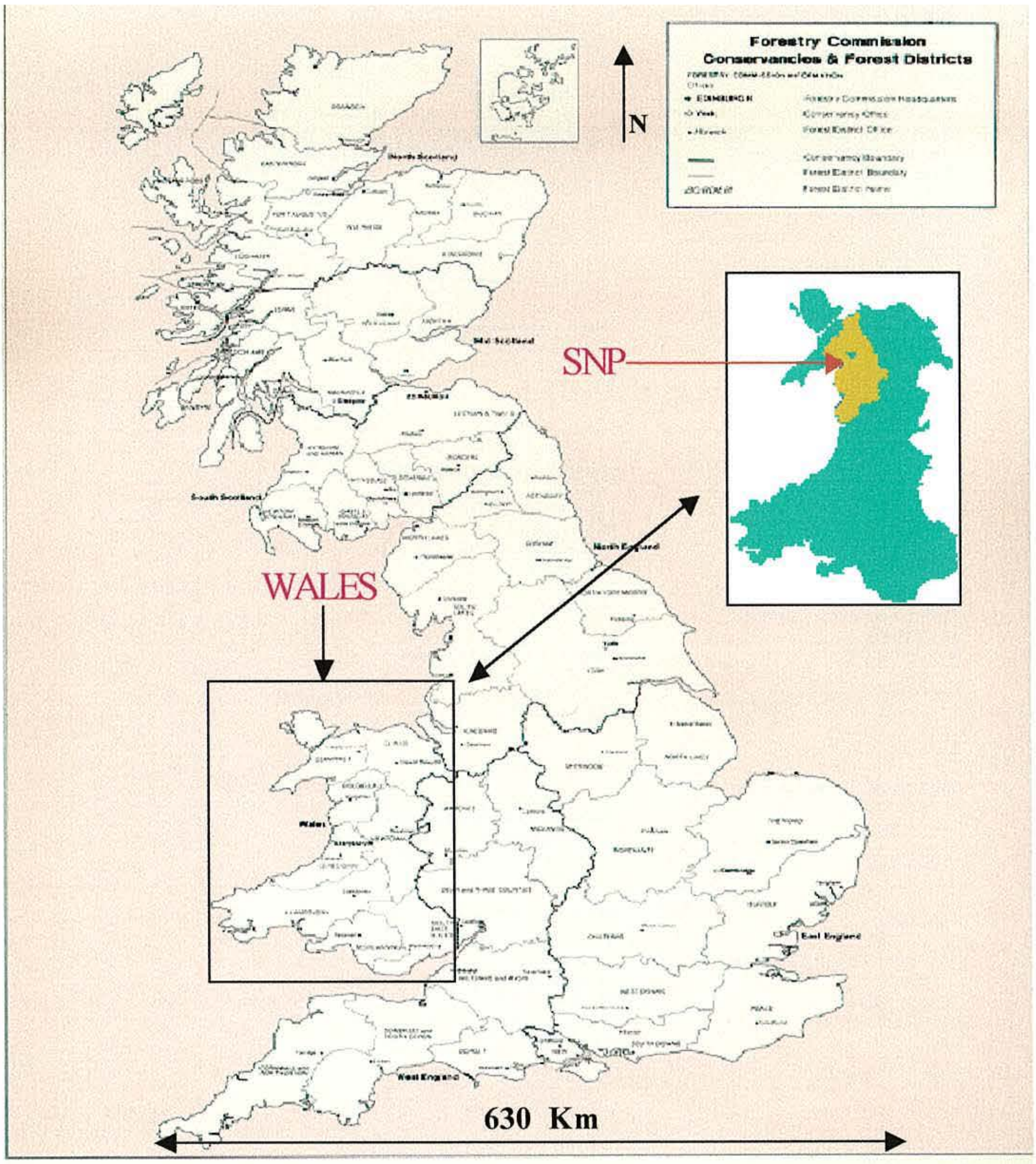
2.3.2 Application of model in a case study

The major objective of this study was the application of this model over a site with forested areas. The DAMS score was combined with the contribution from a forested patch shape, soil class and leaf presence in winter. The contributions of these factors to the WCM were based on the perceived importance of these factors in wind research literature and as expressed in 2.3.4 Method. The Snowdonia National Park was selected as study area to visualise this technique using the IDRISI GIS (Eastman, 1992) as a working platform.

2.3.3 Materials for the study

2.3.3.1 Study area: Snowdonia National park

The Snowdonia National Park (SNP) in Wales, UK was designated as a national park in 1951, covering 838 sq.miles (2171 km^2) mainly of deep valleys, rugged mountains and 23 miles (37 km) of coast line (SNPA, 1999). Cardigan Bay bounds the study area to the west and the Conwy Valley to the east. The River Dyfi estuary forms the southern border whilst the northern border cuts across the Lleyn Peninsula and runs north parallel with the Menai Strait and up to Conwy (Styles, 1993). The location and landuses of the study area are shown in Map 2.3.1 and in Appendix 2.3: Map C, respectively. The Snowdonia National Park contains not only some of the most beautiful scenery in Britain but also a variety of landscapes. It also provides habitats for animals, birds and plants; from 23 miles (37km) of coastline with sand dunes and estuaries; to glacial valleys, the remnants of broadleaved woodlands of oak, ash, rowan and hazel that once covered the mountain slopes, lakes, streams and open mountains (SNPA, 1999). However, a survey by the SNPA in 1978 showed that 85 percent of the 1656 areas of woodland were smaller than 5 hectares and only 4 percent were larger than 50 hectares. The conversion of this primeval forest or 'wild wood' to the present day scatter of woodland fragments began around 3000 BC. A devastating surge of felling in the First World War, and to meet the demand of wood products in the eighteenth and nineteenth centuries were the main reasons of fragmentation of



Map 2.3.1 Showing the location of the Snowdonia National Park (study map) in the map of the British main Isles (Base map adapted from the Forestry Commission, 1990).

wild woodland in SNP (Smith, 1982). Moreover, Edwards (1986) presented three main reasons: coppicing, clear felling and grazing were the disturbances in SNP in the last 300 years. At present grazing is the main limiting factor for natural regeneration (Mulligan, 1999; Kirby, 1989). The Snowdonia National Park Authority (SNPA) has set the target of increasing the area of native woodland within the SNP by 50 percent within the next 50 years to reverse the long term trend of deforestation (SNPA, 1995).

Climate

The climate of the Snowdonia National Park is essentially maritime, being under the influence of Atlantic air masses warmed by passage over the North Atlantic Drift (Mulligan, 1999). The park is one of the wettest parts of the British Isles (Photo 2.3.1), being one of the highest land masses encountered by moisture-laden prevailing south-westerly winds, with an average annual rainfall of 2547 mm, solar radiation-monthly average of 52.3 kW m^2, mean monthly air temperature 5.7^0C (max^m mean monthly- 13.6^0C and min^m mean monthly- 2.1^0C) (Armenteras, 1996). The Snowdonia National Park area lies in wind zone 6 in the revised wind zone map of Britain (Figure 2.2.4; Quine and White, 1993).

Photo 2.3.1 Crib Goch (in SNP) and the summit of Yr Wyddfa in winter (SNPA, 1998).

Landuses

Gibbs and Gittins (1970) imparted the land uses of the Snowdonia National Park (SNP) with 7 main distinct categories and the Centre for Ecology and Hydrology

(CEH, 1990) described land uses of the SNP with 25 categories. Both are presented in the following Tables 2.3.1 and 2.3.2 respectively.

Table 2.3.1 Land owners in SNP area (Gibbs and Gittins, 1970)

Agency	Hectares	Use
Forestry Commission	28,450	Mainly forestry
National Trust	18,373	Mainly agricultural
Nature conservancy (CCW)	486	Conservation / Agriculture
Liverpool Corporation	324	Water Catchments
Economic Forestry Group	1781	Forestry
Meirronydd County Council	526	Recreation
Welsh Office	5423	Agriculture /Research
Other	163497	

Table 2.3.2 Landuses in the Snowdonia National Park (Area is calculated from Centre for Ecology and Hydrology (CEH) (supplied) landuse map).

Land uses	Hectares
1. Sea / Estuary	605.00
2. Inland Water	2045.00
3. Beach and Coastal Bare	630.75
4. Saltmarsh / Seaweed	250.00
5. Grass Heaths	10819.25
6. Mown / Grazed Turf	23190.00
7. Meadows / Verges / Semi-natural	28492.50
8. Rough / Marsh grass	10757.00
9. Moorland grass	34378.25
10. Open shrub moor	14172.25
11. Dense shrub moor	15394.50
12. Bracken	12038.50
13. Dense shrub heath	1845.50
14. Scrub / Orchard	1190.50
15. Deciduous woodland	17779.25
16. Coniferous Woodland	15338.00
17. Upland Bog	2428.00
18. Tilled Land	1451.25
19. Ruderal Weed	No data
20. Suburban / Rural Development	983.00
21. Continuous Urban	11.00
22. Inland Bare Ground	1657.00
23. Felled Forest	No data
24. Lowland Bog	548.25
25. Open Shrub Heath	5530.75

Geology of the area

Snowdonia bears testimony to two cataclysmic geological periods: the Ordovician period and the later Quaternary ice age. In the first period, the oceanic sedimentation with submarine and terrestrial volcanic eruptions formed the future backbone of North Wales. Later during the Quaternary ice age, glaciers eroded the land. The impact of the intense activity on the sedimentary and volcanic rocks created a classic mountain landscape (Williams and Ramsay, 1968).

Soil conditions

The wet uplands are intensely leached and strongly acidic. Brown podozolic soils are found both on gentle slopes and at middle elevations above the lowland zone where less leached brown earth might be typical (Rudeforth *et al.,* 1984). The soil classification of the study area (Snowdonia National Park) is shown in Appendix 2.3: Map C.

Land ownership and uses

The statistics regarding the total area of the Snowdonia National Park and the description of its landuses varies with different authorities because of different measurement mechanisms. The following Table 2.3.3 shows the total area and the method used for measurement by different authorities:

Table 2.3.3 Information about the total area of the Snowdonia National Park.

Total Area of SNP	Method used in measurement	Difference from SNPA measurement	Reference
2171 sq. Km.	Ordnance Survey	Base method	SNPA, 1998
2015.35 sq. Km.	Satellite Image	(-) 7.20%	CEH Land use map
2188.60 sq. Km.	Ordnance Survey	(+) 0.80%	Gibbs and Gittins, 1970

Ownership of land

National Parks in Britain are 'national' in the sense that they are of a national value and importance, but they are not nationally owned. The designation of an area as a

National Park does not affect the ownership of the land, neither does it remove the rights of local communities or imply special rights to the public (SNPA, 1998).

Table 2.3.4 Land ownership in the Snowdonia National Park area (SNPA, 1998).

Land owner	Percent of total land	Remarks
Private	69.9	Potential for afforestation programme
Forestry Commission	15.8	Forestry land for native woodland and plantations
Water Companies	0.9	
National Trust	8.9	
Countryside Council for Wales	1.7	Responsible for SSSI, NNR
Snowdonia National Park Authority	1.25	Policy making
Other groups	1.55	

2.3.3.2 Data Sources

Data for the study were collected from two main sources. The Forestry Commission supplied data for windiness *i.e.* Detailed Aspect Method of Scoring (DAMS) in raster form; the Centre for Ecology and Hydrology (CEH) supplied the maps of the Snowdonia National Park with its land use 1990 and another source of data sets was the School of Agricultural and Forest Sciences (SAFS) of University of Wales, Bangor. SAFS supplied the maps of the Snowdonia National Park with its land use 1990 (original from CEH), soils (digitised from Ordnance map and collected from Silsoe College) and the vector files of the National Park boundary (original from Silsoe College). All data sets were in the IDRISI GIS format.

A. The Forestry Commission

The Detailed Aspect Method of Scoring (DAMS) data for windiness of Snowdonia National Park (SNP) were supplied by the Forestry Commission. They supplied the data with 20 tiles. These maps were concatenated using the IDRISI GIS. Details are in Appendix 2.1.

Description of DAMS

The DAMS score was prepared to indicate windiness for the windthrow hazard classification. The windthrow hazard classification (Miller, 1985; Booth, 1977) has been widely used in Britain by foresters. Here, wind zone, elevation and topex (total exposure) were scaled to a score which was then added to a score for soil class. The windiness scores were produced by simple linear regressions of rates of tatter against elevation (Miller *et al.*, 1987) and by a subjective weighting of the importance of wind zone, elevation and Topex. DAMS scores were constructed from the data collected from 1173 tatter flag sites and used in the analysis.

'*Two equations were fitted to the data. The first equation explained tatter in terms of location, elevation, total Topex, and aspect (identified as one of eight main compass points) and gave an adjusted R^2 of 0.587. These provide a Simple Aspect Method of Scoring (SAMS). The second equation replaced the single aspect term with a weighted average of the eight sector topex values used to form total Topex. This produced the Detailed Aspect Method of Scoring (DAMS)*' (Quine and White, 1993).

DAMS is an outcome of combined weight of wind, elevation, exposure, aspect and funnelling effects. DAMS with soil classes (Miller, 1985) indicates the hazard class for an area. DAMS improved the explanation of tatter (adjusted $R^2 = 0.603$), largely because the treatment of aspect through sector values included a measure of funnelling through valleys. Here it is mentioned that tatter flag data have been used to derive DAMS because they remain the best estimates of windiness for upland Britain (Quine and White, 1993).

Data form

Data on windiness for part of North Wales were supplied as 20 tile maps. The tiles were assembled with the IDRISI module CONCATENATE module to facilitate the analysis of the data sets, and then to create an image for the Snowdonia National Park study area (procedure described in section: 2.4.1). Appendix 2.1: Figure 1A, illustrates the GIS procedures to assemble the tiles into a single map (*stfinal1*), Appendix 2.2 illustrates the macro texts in its 2.2.1 section and the map in final form (*stfinal1*) is presented in Appendix 2.3: Map A.

Effects of DAMS score

Positive and better predictions came from using DAMS for wind hazard classification and the Forestry Commission suggested applying DAMS scores for windiness valuation (Quine and Bell, 1994; Quine, 2000).

B. Centre for Ecology and Hydrology (CEH)

Landuse map of the Snowdonia National Park

The 1990s landuse map (*mos90*) of the Snowdonia National Park was used as a raster data set for the study. The Centre for Ecology and Hydrology (CEH) produced this map. The map was a part of the land cover map of Great Britain which was produced using supervised maximum likelihood classifications of Landsat Thematic Mapper data (Fuller *et al.*, 1994). 25 categories were mentioned in the data sets supplied by CEH in raster form and were available in 25m x 25m resolution. Each 25 m grid cell was assigned a value between 0 and 25 which corresponds to one of the target cover-types in the 25- class data set. According to Fuller (1995), a realistic assessment of land cover map accuracy was 80 to 85%. This map was resampled to match the data set from the Forestry Commission and the resolution of the working images was 50m x 50m. The resampled map of the supplied CEH landuse map (*stsnp90*) is presented in Appendix 2.3: Map B.

C. School of Agricultural and Forest Sciences, University of Wales, Bangor, UK

Data of soil type (*snpsoilt*) and vector data set of the SNP boundary (*snpbound*) were supplied from SAFS, UWB. The land cover data sets in raster form were originally obtained from Silsoe College on behalf of the Countryside Commission and National Park authorities. The soil map with 1420 columns with 2192 rows with a 40m x 40m pixel resolution for 17 soil types were then digitised in SAFS. To put it in line with the map of windiness (after concatenation and resampling) the configuration of the supplied map was changed to 50m x 50m. The resampled map of the soil map (*stsnsoil*) is presented in Appendix 2.3: Map C.

2.3.3.3 Tools used in study

Geographical Information System: IDRISI

The main platform for the study was the IDRISI for Windows, version 2.0 GIS software especially for map analysis (Eastman, 1992).

FRAGSTATS

FRAGSTATS, a computer programme, was used with the IDRISI image to describe and quantify the landscape structure (McGarigal and Marks, 1995). This computer programme enables the computation of various metrics of a landscape (Appendix 2.6). This study analyse forest patch shape in order to estimate how much the patch shape is different from a circle. Every patch identified through FRAGSTATS had its perimeter and the area it covered provided.

2.3.4 Method

This part of the study presents methodology of integration of spatial data sets and techniques using GIS functions to generate the WCM. The purpose is to map the spatial distribution of different components (patch shape, soil class and leaf presence in winter) used in this system as well as to integrate them with DAMS data set in a simple map. The data considered in this study were extracted from a national scale to local planning of forest management by simulating the WCM. Four combinations were used to draw four WCMs. Flow diagrams and the macro statements for the simulation of the new WCMs with four combinations in IDRISI, GIS format are presented in Appendix 2.1 and Appendix 2.2 respectively.

2.3.4.1 Factors combining in WCM

A broad spectrum of factors was taken into consideration. The highest contribution combinations will be with the worst soil class with respect to plant support (Appendix 2.5), elongated patch shape and presence of leaves (evergreen) in winter. These combinations show the areas which are the windiest for site/species suitability. Four scenarios of contribution combinations of stated factors are presented in Table 2.3.5.

This study demonstrates the integration of spatial data considering DAMS, soil, patch shape (ratio between the patch area and the area of a circle with the same perimeter as the patch) and leaf presence in winter with WCM using GIS. However, patch orientation, patch size and patch edge: area ratios are important factors to windiness (Price, 2001, pers. comm..). Patch orientation indicates from which directions patch will receive wind with respect to season. Patch size and edge: area ratio indicate the amount of edge for a patch which is vulnerable to endemic wind for example: four 1 hectare patches of given shape have twice the edge-area ratio of one 4-hectare patch (Price, 2001, pers. comm..). These factors are not included in this study and could be subject to further research.

DAMS

Pyatt and Suarez (1997) introduced a broad methodology using the Ecological Site Classification (ESC) which is applicable to all kinds of woodlands, from the plantations of a single species through the range to semi-natural woodlands of many species in Great Britain. The suitability ratings of each species depend upon the five climatic and soil factors: accumulated temperature (AT), moisture deficit (MD), windiness (DAMS), soil moisture regime (SMR) and soil nutrient regime (SNR). Ecological site classification used the windiness (DAMS) with the accumulated temperature (AT) and moisture deficit (MD) with a scale of optimal, suitable and unsuitable for choice of species for a site.

This use of DAMS in ESC is specific in details for the Grampian region of Scotland, but only provides broad guidance for average conditions elsewhere in the UK (Pyatt and Suarez, 1997). The contribution of comprising factors in DAMS estimation is described in the following way: wind zone 35.13%, elevation 27.03%, Topex 21.63% and aspect 16.21% = 100%.

Soil

Millar (1985) used the soil factor as a 25% contributor (in wind hazard classification total highest hazard score is 43 and the highest score for soil is 10) in assessment of wind hazard classification. To indicate the contribution of soil in

WCM- expert advice (Quine, 2001) also supported the same. To demonstrate the effects of soil factors a range 10% to 25% increase of DAMS was considered to add with windiness scale in four combinations present in Table 2.3.5.

Patch shape

Patch shape contribution in wind acceleration, retardation and diversion is obvious. Quantifying the shape of patches, in forest management with a view to windiness, is a new approach. The Forestry Commission measured windiness (DAMS) and considered wind speed, elevation, aspect and funnelling effect. It is apparent that patch shape has an important effect on wind flow. Quine (1994) in his 'rethinking windthrow models' suggested that patch crown shape and root form should be considered as progressive components of vulnerability of windthrow but did not mention how to quantify the patch shape of the forest. To date, no studies have been published on patch shape contribution to windiness particularly for the Snowdonia National Park of Wales, UK. The range 15% to 25% increase of DAMS was considered as patch shape contributions in the WCM scenarios (Table 2.3.5).

Leaf presence in winter

Leaf presence in winter may be a potential factor (Quine, 2001) to consider indicating species-site suitability. In winter the gales and the endemic wind appeared more than during the summer in Great Britain. To date, no studies have been published on leaf contribution to windiness particularly for the Snowdonia National Park of Wales, UK. Assuming leaf absence reduces the vulnerability of windblown. As all the study area is with conifer plantation it may not contribute much in the differentiation of four WCMs. The contribution (1%) of leaf is an assumption. It may be higher. Field based experiment is needed to quantify the contribution which should be subject to further research. The leaf presence factor is included, so that if the model is run for species with different characteristics, the factor can be adjusted.

Table 2.3.5 Illustrating combinations of factors with indicating a percentage increase of DAMS for four scenarios of the study.

Combination	Patch shape	Soil class	Leaf presence
Scenario 1 (P1) for WCM1	25%	25%	01%
Scenario 2 (P2) for WCM2	25%	20%	01%
Scenario 3 (P3) for WCM3	20%	15%	01%
Scenario 4 (P4) for WCM4	15%	10%	01%

C. Mathematical expression for single unit (one) WCM score

Four mathematical expressions for single WCM score with four combination scenarios are described below:

$$1\ WCM1 = (1 + 0.25 \times P + 0.25 \times S + 0.01 \times L)\ DAMS$$
$$1\ WCM2 = (1 + 0.25 \times P + 0.20 \times S + 0.01 \times L)\ DAMS$$
$$1\ WCM3 = (1 + 0.20 \times P + 0.15 \times S + 0.01 \times L)\ DAMS$$
$$1\ WCM4 = (1 + 0.15 \times P + 0.10 \times S + 0.01 \times L)\ DAMS$$

where, P = Patch shape, S = Soil class, L = Leaf presence in winter

2.3.4.2 Data analysis

IDRISI for windows version 2 (IDRISI, 1997) was used as a working GIS platform, installed in an Intel© based Personal Computer, to analyse the data sets for generating the WCM.

A. Modification of supplied maps

Concatenation

The Forestry Commission supplied the DAMS data sets in tile form. The CONCAT function was used to make a whole map (*stfinal1*) of the DAMS data set through pasting together. This function of IDRISI allows the pasting together of images to form a larger one. GIS procedures followed in this concatenation are described with a flow diagram in Appendix 2.1 Figure 1A and the macro text of operation in IDRISI format placed in Appendix 2.2 of section 2.2.1.

Resample

The supplied maps of land use (*mos90*) and soil type (*snpsoilt*) of the study area were resampled with the GIS function RESAMPLE. This function registers the data in one grid system to another specified grid system covering the same area (Eastman, 1992). The new map configurations are presented in Appendix 2.3 and the GIS procedures followed for new maps are described in Appendix 2.1 Figure 1B. A correspondence file (*alamin*) was created to describe the information of a set of points about their positions in the old grid system and the position they should take in the new one.

FRAGSTATS image

The spatial analysis programme FRAGSTATS version 2.0 was used to quantify the patches in the image. FRAGSTATS accepts images in several forms, depending on whether the image contains background and whether the landscape contains a border. An image may include background; an undefined area either interior or exterior to the landscape border; a strip of land surrounding the landscape of interest within which patches have been delineated and classified (McGarigal and Marks, 1995; Gkaraveli, 1999). The basic procedure of preparing the input map for FRAGSTAT was adopted from McGarigal and Marks (1995) and Gkaraveli (1999). The resampled land use map of the study area (*stsnp90*) was reclassified into a Boolean image to indicate only conifer plantations in the study area using the RECLASS function. Outside the study area was coded as background in this process so that it was not treated as a patch itself, but formatted as a distinct edge. The GIS procedures followed in this process are presented in summary form in Appendix 2.1 Figure 1C and macro texts are presented in Appendix 2.2 section 2.2.3.

DAMS data map for study area

The DAMS data map for the study area (*windsnp*) was created by combining the landuse map (*mos90*) and the concatenated DAMS data map (*stfinal1*) using RESAMPLE, INITIAL, RECLASS and OVERLAY functions of GIS. The flow diagram of creating the map (*windsnp*) is presented in Appendix 2.1 Figure 1B and macro texts are presented in Appendix 2.2 section 2.2.2

2.3.4.3 Procedures in combining the factors in WCM simulation

Worked examples of calculating the four combination scenarios of WCM are presented in section 2.3.4.7. Detailed procedures for combining factors are presented in the following:

A. *Patch Shape*

Mathematical expression of models stated that patch shape is to be quantified as an increase with respect to 25%, 25%, 20%, and 15% of DAMS score. The patches in the conifer plantation of the study area were the study patches for shape quantification. Patch shape was measured through simple geometrical analysis. Specific patches were identified with FRAGSTATS output image (*coniout*). Patch perimeter and area were calculated through PERIM and AREA functions of GIS respectively. Maps names are presented in brackets with *italic* letter with the description of the calculation text.

Mathematical approach to calculate patch shape

Four steps were followed to quantify patch shape after getting the output map of FRAGSTATS (*coniout*).

Step 1. *Calculation of area of a circle having the same perimeter as a patch*

If the patch has a boundary of random orientation then the ratio of its representation by horizontal and vertical pixel boundaries to its true length is 1.273:1. Hence, to get the radius of a circle having the same perimeter of a patch, the perimeter of the patch is divided by the constant 1.273 (Adjusted perimeter). The formula for the perimeter of a patch = $2\pi r$, where π is a constant with a value of 3.142 (approx.) and r stands for radius. Adjusted perimeter = Perimeter of patch / 1.273. Radius r was calculated from the adjusted perimeter of the patch, r = Adjusted perimeter / 2π (*conir1*). The area of a circle = πr^2. SCALAR function of the GIS IDRISI was used to calculate the area of a circle with the same perimeter as the patch perimeter (*conicir2*). Map analysis in Appendix 2.1 Figure 1D.

Step 2. *Calculation of the ratio between the patch area and the area of a circle with the same perimeter as the patch*

The ratio between the real area of the patch (calculated by the AREA function of GIS) and the area of the circle having the same perimeter of the patch (calculated in step1) was measured with OVERLAY (divide) function of GIS (*coniprop*). This ratio described the difference of a patch shape from a circle. If a patch is truly circular, then patch area / circle area = 1, which would be the best one to resist the wind. *Here it is noted that as a worst case for shapes: patch area / circle area = 0, is not incorporated in this model.* Hence the worst case may be: patch area / circle area = up to 0.001 but not 0.

Example: 17500 sq. metre / 31424 sq. metre = 0.56

Step 3. *Contribution of patch shape*

This stage calculated the effects of patch shape according to the combination scenarios. The following formulae are used to calculate the final contribution of patch shape with respect to the scenarios of Table 2.3.5:

1 - Results of Step 2 for P1 (25% increase of DAMS) (*coniin25*)

1 - Results of Step 2 for P2 (25% increase of DAMS) (*coniin25*)

1 - Results of Step 2 for P3 (20% increase of DAMS) (*coniin20*)

1 - Results of Step 2 for P4 (15% increase of DAMS) (*coniin15*)

Example: patch area / circle area = 0.56, then the patch effect = 1-0.56 = 0.44

Step 4. *Calculation of contribution of patch shape according to combination scenarios*

Four combination scenarios P1, P2, P3, and P4 showed 25%, 25%, 20%, and 15% increase of DAMS as patch shape contributions respectively. The procedures followed in the calculation of contribution with respect to combination scenarios are given below:

Results of Step 3 x 0.25 for P1 (25% increase of DAMS) (*conicr25*)
Results of Step 3 x 0.25 for P2 (25% increase of DAMS) (*conicr25*)
Results of Step 3 x 0.20 for P3 (20% increase of DAMS) (*conicr20*)
Results of Step 3 x 0.15 for P4 (15% increase of DAMS) (*conicr15*)

Example: If patch effect 0.44 then with P1, (0.44 x 0.25) DAMS = 0.11x DAMS

Maps describing the calculations of patch shape

Patch shape contribution was calculated using the SCALAR function of the GIS. SCALAR is a function which can perform arithmetic on images by adding, subtracting, multiplying, dividing or exponentiating the pixels in the input image by a constant value (Eastman, 1992). GIS procedures followed to calculate the contributions of patch shape with scenarios of Table 2.3.5 are described with the flow diagram in Appendix 2.1 Figures 1D and 1E. Macro texts are presented in Appendix 2.2 section 2.2.4.

B. *Soil Classes*

Soil class for each patch was also considered because of its contribution to the penetration of roots which provide substantial resistance against wind blow. Miller (1985) presented the soil score of soil classes to construct the windthrow hazard zone. The scoring of soil classes has been done according to less penetrability to high penetrability of tree roots in soil. With reference to his works, this study presented a score of soil classes, weighting wind resistant capacity of soil in relation to root penetration. The scores of soil classes are presented in Appendix 2.5. These scores were then combined according to Table 2.3.5.

Mathematical approach to combine the soil scores

The calculation procedure for combining soil scores is described with the following three steps:

Step 1. *Identification of soil classes, scored with tabulated (Appendix 2.5) score*
Soil classes were identified from the resampled soil map of the Snowdonia National Park (*stsnsoil*) and then reclassed with five Boolean maps indicating five score classes (1, 0.75, 0.50, 0.25 and 0.00). The maps are presented as *rcouts1*, *rcouts75*, *rcouts50*, *rcouts25*, and *rcouts0*. The following formula is used to calculate the final contribution of with respect to the soil classes:

1 - Soil score of soil class (for P1, P2, P3 and P4)

Example: Humic ranker score in Appendix 2.5 is 0, so the contribution, 1-0 = 1

Step 2. *Calculation of contribution of soil class according to combination scenarios*
Four combination scenarios showed 25%, 20%, 15%, and 10% increase of DAMS as soil class contributions respectively. Every soil class contribution was combined with the contribution proportion indicated in scenarios of Table 2.3.5. The procedures followed in the calculation of contributions with respect to combination scenarios are given below:

Result of step 2 x 0.25 for P1 (25% increase of DAMS)
Result of step 2 x 0.20 for P2 (20% increase of DAMS)
Result of step 2 x 0.15 for P3 (15% increase of DAMS)
Result of step 2 x 0.10 for P4 (10% increase of DAMS)

Example: Humic ranker contribution with P1 (1 x 0.25) DAMS = 0.25 x DAMS

Maps describing the calculations of combined soil scores
The soil map (*Snpsoilt*) of the Snowdonia National Park was resampled with the GIS function RESAMPLE and then a cross tabulation was performed with the reclassed map of the FRAGSTATS output map (*coniout*). These two maps were the basic maps to derive the weighted soil score. RECLASS, CROSSTAB, SCALAR and OVERLAY functions were used to create final maps indicating 25%, 20%, 15% and 10% increase of DAMS as contribution of soil over the patches of conifer plantations in the study area. GIS procedures in preparing maps for calculating the soil contributions are presented in summary form as a flow

diagram in Appendix 2.1. Macro languages in IDRISI format, for this part are also presented in Appendix 2.2 section 2.2.5.

C. Leaf presence in winter

SCALAR function was used to include this factor in combination with other factors, as all the study area is comprised of conifer plantation. Final maps with leaf contributions are *cr25251*, *cr25201*, *cr20151* and *cr15101* (Map analysis in Appendix 2.1 Figure 1I). Macro texts are presented in Appendix 2.2 section 2.2.6.

Example: Leaf presence contribution is 1% so add 0.01 for single DAMS score

2.3.4.4 Combining the factors in WCM

Patch shape, soil class and leaf presence in winter contributions, were added with single unit DAMS score *i.e.* 1 (Final 1, 2, 3 and 4). Then every pixel with DAMS score (Map *Coni3win*) for the conifer stand was multiplied with Final 1, 2, 3 and 4 maps to get new composite score for WCMs. GIS procedures for creating maps *WCM1, WCM 2, WCM 3, WCM 4* are presented in Appendix 2.1 Figure 1I and macro texts are presented in Appendix 2.2 section 2.2.6.

Example: If DAMS is 10.5 then

$$WCM1 = (1+0.11+0.25+0.01) \times 10.5$$
$$= 14.39$$

2.3.4.5 Potential land locations for the Snowdonia National Park Authority (SNPA) for 20 years to create native woodland according to WCM

The conifer plantations which lie in windy situations may have potential for being replaced by native woodland. Snowdonia National Park Authority (SNPA) required 58 hectares of land per year to create native woodland in a 20-year programme *i.e.* 1160 hectares. Again, it is not wise to consider only the threshold limit of DAMS to identify the unsuitable area for conifer plantations of the study area because the proper threshold would be different for each and every combination of patch shape, leaf presence and soil conditions (Price, 2001).

Therefore, the required land locations (1160 hectares) were selected from the areas that lay from the highest WCM score to the lower until the area reached was close to 1160 hectares. Four WCM scenarios were generated to visualize four alternative potential areas in the present conifer plantations of the Snowdonia National Park.

2.3.4.6 Locate areas over the windiness limit ESC with average patch shape, soil class and leaf presence contributions

Pyatt and Suarez (1997) reported that the limit of suitability for Sitka spruce was 22 (DAMS score). In their technical paper, it was not mentioned how they selected this limit. It is assumed that *too windy* situations may be unsuitable for the growth of the tree species, and this situation may prevail for areas with DAMS score over 22.

This section of the study considered the limit of suitability produced by Pyatt and Suarez (1997) and also taking the same DAMS score (limit of suitability) to test a methodology to estimate the average contributions of component factors per pixel to find out a limit of suitability for WCM. Thus,

Average shape effect = Total patch shapes effects / Total pixel number of patches;
Average soil effect = Total patch soil effects / Total pixel number of patches;
Average leaf effect = Total patch leaf effects / Total pixel number of patches.

Four limits of suitability for four scenarios of WCM were calculated with the following formula:

$$\text{Limit of suitability} = 22 \times \{1 + (\text{sum of average contribution of factors})\}$$

22 (DAMS score) is the limit of suitability for Sitka spruce prescribed by Pyatt and Suarez (1997) for Great Britain. The new limits of suitability for scenarios of WCM are considered the factors: patch shape, soil and leaf effects, which were not included by Pyatt and Suarez (1997). Four maps were generated using GIS to locate the area above the limit of suitability for the four scenarios.

2.3.4.7 Worked examples of calculating WCM

Table 2.3.6 illustrates how individual patch shapes are incorporated in the model with soil class and Table 2.3.7 demonstrates the combinations of patch shape, soil classes and leaf presence in winter with four combination scenarios, assuming all the pixels of the patches have a 10.5 DAMS score.

Table 2.3.6 Illustrates the patch shape calculation with respect to individual patches and soil classes.

PID	Peri meter	Adjusted Perimeter	Radius metre	C. Area sq.m	Real Area hectare	Real Area sq.m	R.Area /C.Area	Shape	Soil type
a	b	c = b/1.273	$d=c/2\pi$	$e=\pi d^2$	f	g	h = g/e	i	j
6	400	314.22	50.00	7856	0.75	7500	0.95	Nearly circular	Humic Ranker
162	800	628.44	100.01	31424	1.75	17500	0.56	Elongated	Brown Earth
2825	600	471.33	75.00	17676	1.25	12500	0.71	Oval	Raw oligo-amorphous peat

Table 2.3.7 Illustrates a worked example for simulating WCMs combining patch shape, soil class and leaf presence with DAMS score. Factors are taken from Table 2.3.5.

Models	Patch ID	Adjusted Perim	R.Area / C Area	Patch effect	Contribution w. r. to 0.25	Soil Type	Soil score	Soil effect	Contribution w. r. to 0.25	Patch shape Soil effect	Leaf presence	Add with value 1.00	DAMS	WCM
		a	b	c = 1-b	d =c x 0.25	e	f	g = 1-f	h = g x 0.25	i = d+h	j	k =1 + (i + j)	l	m = l x k
WCM1 25+25+01	6	314.22	0.955	0.045	0.011	Humic Ranker	0.000	1.000	0.250	0.261	0.010	1.271	10.500	13.349
	162	628.44	0.557	0.443	0.111	Brown Earth	1.000	0.000	0.000	0.111	0.010	1.121	10.500	11.768
	2825	471.33	0.707	0.293	0.073	Peat	0.000	1.000	0.250	0.323	0.010	1.333	10.500	13.999
					Contribution w. r. to 0.25				**Contribution w. r. to 0.20**					
WCM2 25+20+01	6	314.22	0.955	0.045	0.011	Humic Ranker	0.000	1.000	0.2000	0.211	0.010	1.221	10.500	12.824
	162	628.44	0.557	0.443	0.111	Brown Earth	1.000	0.000	0.0000	0.111	0.010	1.121	10.500	11.768
	2825	471.33	0.707	0.293	0.073	Peat	0.000	1.000	0.2000	0.273	0.010	1.283	10.500	13.474
					Contribution w. r. to 0.2				**Contribution w. r. to 0.15**					
WCM3 20+15+01	6	314.22	0.955	0.045	0.009	Humic Ranker	0.000	1.000	0.1500	0.159	0.010	1.169	10.500	12.275
	162	628.44	0.557	0.443	0.089	Brown Earth	1.000	0.000	0.0000	0.089	0.010	1.099	10.500	11.535
	2825	471.33	0.707	0.293	0.059	Peat	0.000	1.000	0.1500	0.209	0.010	1.219	10.500	12.795
					Contribution w. r. to 0.15				**Contribution w. r. to 0.10**					
WCM4 15+10+01	6	314.22	0.955	0.045	0.007	Humic Ranker	0.000	1.000	0.100	0.107	0.010	1.117	10.500	11.726
	162	628.44	0.557	0.443	0.066	Brown Earth	1.000	0.000	0.000	0.066	0.010	1.076	10.500	11.303
	2825	471.33	0.707	0.293	0.044	Peat	0.000	1.000	0.100	0.144	0.010	1.154	10.500	12.116

2.4 Results

This part of the study presents the performances of GIS functions in integrating spatial data sets and techniques for the simulation of the wind composite model (WCM) with four scenarios.

2.4.1 Pre processing map assemblage

Concatenation

The Forestry Commission supplied the DAMS data set in 20 tiles of 20 x 20 km size. All the supplied maps were pasted together to produce a single map of DAMS data set using CONCATE function of GIS. The resultant map *Stfinal1* is presented in Appendix 2.3: Map A. The dimension of the map (*Stfinal1)* is 100 km x 100 km and includes the Snowdonia National Park. This is the main raw data map of the DAMS data set for the study.

Restoration of maps

The land use map (*mos90*) and the soil map (*snpsoilt*) of the Snowdonia National Park were in raster form and the boundary map (*snpbound*) was in vector form. All the stated maps were reformatted with the function RESAMPLE. The *snpbound* was used to restore a new geo-register location of all supplied maps. Eventually, a map named *windsnp* was created with the DAMS data set. This map was a combination of the resampled landuse map and the DAMS data set with the specific boundary layout for the study area. The location and DAMS score as z value of every pixel was indicated in the map in the IDRISI GIS format. The resampled maps *stsnp90* (from *mos90*), *stsnsoil* (from *snpsoilt*) and *windsnp* are presented in Appendix 2.3: Map B, Map C and Map D respectively.

FRAGSTAT map

The FRAGSTAT input map (*coni4*) and the output map (*coniout*) with the identification number of all conifer patches in the study area are presented in Appendix 2.3. The study considered conifer plantations (composed of 94% of Sitka spruce) of the study area as the study species for the model simulation. The FRAGSTAT output map (*coniout*) also provides the patch indices and is presented in Appendix 2.6 as an example of a few patch matrices. 2845 patches of different shape were identified with the FRAGSTAT output map (*coniout*) in the study area. Input and output FRAGSTAT maps are presented in Appendix 2.3: Map E and Map F respectively.

2.4.2 Wind composite model (WCM) simulation

The new WCM required combining contribution stated in Table 2.3.5 of patch shape, soil classes and leaf presence with DAMS data.

2.4.2.1 Patch shape contribution to WCM

The contributions of patch shape in generating four combination scenarios: WCM1 (P1), WCM2 (P2), WCM3 (P3), WCM4 (P4) were 25%, 25%, 20% and 15% addition of DAMS score respectively. The input map was *coniout*. The area of every patch was calculated with AREA function of GIS and the resultant map was *coniarea*. The resulting map (*coniperm)* indicating the perimeter of every patch which was calculated by PERIM, a function of GIS. The area of circles with the perimeter of patches in *coniout* map was calculated with SCALAR and the resultant map was *conicir2*. The ratio between the area of the patch and the area of the circle (calculated from the same perimeter) was calculated and the resultant map was *coniprop*. The percentage contribution of patch shape in WCM1 and WCM2 is the same so the resultant map of patch shape (*conin25*) for WCM1 (P1) would be considered for WCM2 (P2) too.

The maps *coniarea, coniperm, coniprop* were the processed maps in this stage. The final output maps to combine the contribution of the patch shape were *coniin15*, *coniin20*, and *coniin25* are presented in Appendix 2.3: Map G, Map H, and Map I respectively.

2.4.2.2 Soil class contribution to WCM

Soil class contributions in four combination scenarios: WCM1 (P1), WCM2 (P2), WCM3 (P3), WCM4 (P4) were 25%, 20%, 15% and 10% increase of DAMS score respectively. The input maps were *coniout* (FRAGSTAT output map) and *stsnsoil* (resampled supplied soil map) of the study area. Input maps were taken together and classified with respect to the score allocated in the soil class table (Appendix 2.5). Five resultant maps *rcouts1*, *rcouts75*, *rcouts50*, *rcouts25*, and *rcouts0* were created with soil class values of 1.00, 0.75, 0.50, 0.25, and 0.00 using RECLASS and CROSSTAB functions of GIS. These maps are presented in Appendix 2.3: Map J, Map K, Map L, Map M, and Map N. Then combining the contribution of soil classes was done by SCALAR function of GIS with 25% (for P1), 20% (for P2), 15% for (P3) and 10% (P4). Four final maps were created named *solovf25*, *solovf15*20, *solovf15* and *solovf10* indicating 25%, 20%, 15% and 10% addition of DAMS score as contribution of soil to wind composite model. Example soil maps, *solovf25 and solovf10* are presented in Appendix 2.3: Map O and Map P respectively.

2.4.2.3 Leaf (presence in winter) contribution to WCM

Leaf presence in winter was also calculated with respect to four combination scenarios: WCM1 (P1), WCM2 (P2), WCM3 (P3), and WCM4 (P4). SCALAR function was used to add the leaf contribution (0.01) with four combination scenarios. The combining contribution of leaf presence with other factors is presented in *cr15101, crso20151, cr25201,* and *cr25251*. Maps are presented in Appendix 2.3: Map Q, Map R, Map S, and Map T respectively.

2.4.2.4 WCM final maps with four combination scenarios

The contributions of all the factors were combined with the OVERLAY function of GIS with every pixel of DAMS data placed in the supplied map. Four maps named *wcm1*, *wcm2*, *wcm3*, and *wcm4* were created with respect to the four combination scenarios WCM1 (P1), WCM2 (P2), WCM3 (P3), WCM4 (P4) respectively (presented in Appendix 2.3: Map V, Map W, Map X, and Map Y respectively).

2.4.3 Impact of four combination scenarios of WCM

2.4.3.1 Pixel distribution in four combination scenarios of WCM

The contributions of patch shape, soil classes and leaf presence in winter with windiness (DAMS) in conifer plantations of the SNP were demonstrated with the four scenarios of WCM (WCM1, WCM2, WCM3 and WCM4). All the maps were reclassified with unit (1.00) class interval. Figure 2.4.1 illustrates the pixel distributions of new WCM with four scenarios. This graph shows how the distribution of pixels scores changes as the factors in Table 2.3.5 are added to the DAMS score.

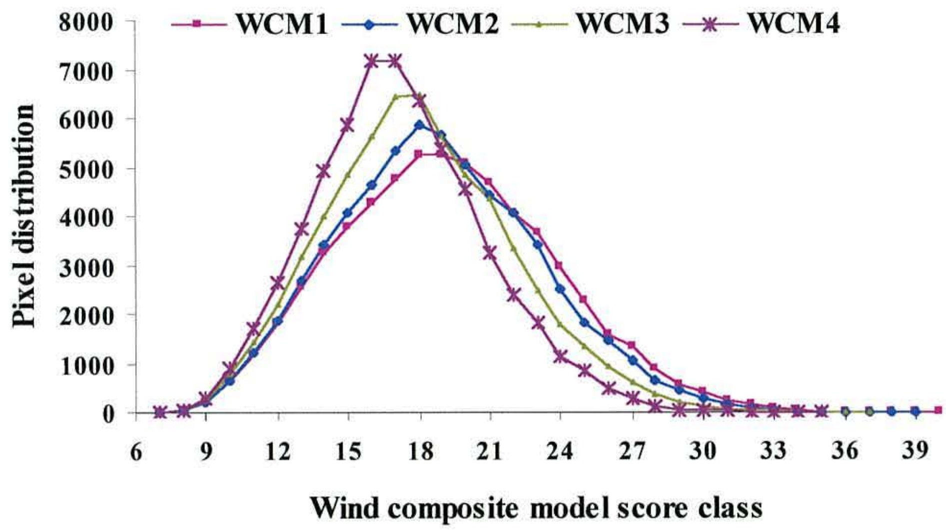


Figure 2.4.1 Pixel distribution in maps for conifer species with respect to four combination scenarios WCM1 (P1), WCM2 (P2), WCM3 (P3), WCM4 (P4).

2.4.3.2 Areas available for other land-use than conifer in the study area

Four maps were generated to locate the areas that may be potential for native woodland for the Snowdonia National Park Authority (SNPA). The required land locations (1160 hectares) were selected from the areas that lay from the highest WCM score to the lowest until the area reached 1160 hectares. Table 2.4.1 shows how the WCM scores would have to be adjusted under the four scenarios in order to find the target area of 1160 hectares. Maps were generated and are presented in Appendix 2.3: Map Z, Map AA, Map AB and Map AC.

Table 2.4.1 Illustrates the land available with respect to the wind composite model scenarios for choosing areas in the SNP. Coloured areas may be potential for other landuse than conifer (for SNP). Target area 1160ha, section 2.3.4.5 page 45.

WCM scores	Combination scenarios			
	WCM1 hectare	WCM2 hectare	WCM3 hectare	WCM4 hectare
6	1.25	1.25	1.25	1.25
7	7.75	8.25	8.75	9.25
8	49.5	49.5	57	70.75
9	160.25	161.75	189.25	223
10	300	306	359.75	424.5
11	456.5	468	546.75	665
12	644	669	791.25	941.25
13	813	853.5	1000.5	1237.5
14	951.25	1024	1212.5	1467
15	1075.5	1160.25	1409	1791.25
16	1196.25	1340	1611	1792.25
17	1317.5	1473	1624.75	1588.25
18	1313	1420	1404.25	1346.25
19	1279.25	1264.75	1210	1144
20	1170.75	1113.75	1095.75	818.25
21	1024.5	1017.25	835.5	606.5
22	921.25	856.75	622.25	458
23	745.5	631	448.25	289.75
24	569.5	460.5	340	213
25	394.5	365	232.25	122
26	334.5	261.75	151.75	71
27	220.5	165.75	88.25	31
28	146	114.75	47.75	12
29	101	69.75	26	7.75
30	57	37.25	11.5	6.25
31	38.25	23	6.25	0.75
32	25.5	11.25	5.25	0
33	12.5	4.5	1	0.25
34	4.25	4.5	0.25	0.25
35	5	1.75	0.25	
36	2.25	0.25		
37	0	0		
38	0.25	0.25		
39	0.25			
Total marked area	1341.75	1520.25	1358.75	1212.00

2.4.3.3 Limit of suitability for Sitka spruce

Average factors effects

Table 2.4.2 shows the average contributions of component factors per pixel for the conifer plantation of the study area.

Table 2.4.2 Illustrates average contributions of component factors effects per pixel.

Factors	Total Pixel numbers	Total effects	Average effect	25%	20%	15%	10%
a	b	c	D = c / b	D x 0.25	D x 0.20	D x 0.15	D x 0.10
Patch shape	61353	929.19	0.015	0.004	0.003	0.002	
Soil class	61353	31264.50	0.51	0.127	0.102	0.076	0.051
Leaf presence	61353	613.53	0.01				

Limit of suitability with four scenarios of WCM for Sitka spruce

Table 2.4.3 illustrates the limit of suitability for Sitka spruce and available land over the limit with four scenarios for the wind composite model (WCM). Using GIS, four maps were generated (Appendix 2.3: AD, AE, AF and AG) locating the land available over the limit of suitability for Sitka spruce in the study area with WCM.

Table 2.4.3 Limit of suitability for Sitka spruce with four scenarios of WCM.

WCM Scenarios	Average patch effect per pixel	Average soil effect per pixel	Average leaf effect per pixel	Total effect per pixel	1 + Total effect	Limit of suitability	Land over (g) limit
a	b	c	d	e = b+c+d	f = 1 + e	g = f x 22	hectare
WCM1	0.004	0.127	0.010	0.141	1.141	25.106	1288
WCM2	0.004	0.102	0.010	0.116	1.116	24.546	1246
WCM3	0.003	0.076	0.010	0.089	1.089	23.968	924
WCM4	0.002	0.051	0.010	0.063	1.063	23.391	626

2.5 Discussion

The primary purpose of the study is to develop a methodology to analyse the contribution of the spatial data and geographical information systems to make a strategic forest management plan at a regional level. This part of the study focused on efficiency and accuracy of GIS functions and the versatile uses of spatial data through GIS for effective management. The new wind composite model (WCM) demonstrates how a forest manager may foresee a future course of action with spatial data management using GIS from a national scale to a regional planning level. MACRO, a GIS function, also provides an opportunity to regulate future planning with the facility to change any variable in a forest area on a week-by-week basis.

2.5.1 WCM model simulation and the performance of GIS modules

The Forestry Commission of Great Britain developed DAMS as the windiness scale to indicate an area under threat of windthrow hazard. DAMS was developed in the last decade and is considered as the most effective form of judgement about windiness in forest areas. However, it had limitations in forecasting the vulnerability of windthrow for existing plantations, because it did not incorporate some tree factors, especially patch shape. Endemic wind is considered a major factor in forest management because of its span of contributions as a damaging agent as well as dispersal of seeds. Recent windthrow in France and Germany led to the consideration of the role of wind in forest management. However, there appear to be no forest management systems that use wind disturbance of natural forests alone as a management opportunity (Quine *et al.*, 1999).

The wind composite model (WCM) is a multi-factor model incorporating patch shape, soil class and leaf presence in winter with DAMS data sets to indicate species suitability in the specified area. Pyatt and Suarez (1997) produced a multi-dimension feature space model ESC (Ecological Site Classification) specifying thresholds for windiness. WCM indicates the *too windy* situation for Sitka spruce for the study area but not prescribed as a firm management tool because this is a test of methodology, and important factors like patch orientation, patch area and edge: area ratios are not included and all factors in the model are not validated with field study.

The four combination scenarios of WCM set out four alternatives for the forest manager. This indicates that GIS can provide several options for the forest manager to compare and subsequently to reach an appropriate decision. The combining procedures with three factors also enable the consideration of several factors to produce an effective model within the platform of GIS.

Incorporating the FRAGSTATS map in IDRISI GIS, demonstrated that it is able to adapt and interchange with other techniques (such as statistical software) and data. The GIS and statistical software (FRAGSTATS) enabled the management and analysis of a large number of data points through the use of macros.

2.5.2 Integrating spatial data sets

The basic map layers were created from the supplied data set by assembling the separate DAMS maps (CONCAT) and also repositioning and rescaling the map (RESAMPLE) with the desired scale of the study. The assembling function of GIS (CONCAT), joins smaller maps together to make a larger one as in the way the manager desires: *stfinal1* (Appendix 2.3: Map A) is a map of this kind created in this study. CONCAT is a powerful tool to arrange and add many smaller maps into a single one.

RESAMPLE can work with numerous reference systems with metre, feet, mile, kilometre, degree or radian in linear, quadratic and cubic resample options. The resolution of the map also changed with the application of this module. This module helps the forest manager to create a desired map from any available map in raster or vector form with any spatial resolution of the area concerned. The desired maps created in this study were *stsnp90* (Appendix 2.3: Map B) and *stsnsoil* (Appendix 2.3: Map C) in raster form and *snpbound* in vector form.

The opposite of the assembling function is to pick up a desired portion from a map (WINDOW), which was used to create *windsnp* (Appendix 2.3: Map D) the map of the study area with the DAMS data set.

FRAGSTATS requires images with a background or a border of landscape. To prepare an input FRAGSTATS map, a Boolean map of landuse (RECLASS) was created first in this study. Then the arithmetic calculation (SCALAR) with a negative value of 1 (MULTIPLY) was done and eventually two Boolean maps were added together with 'OR' logic function (OVERLAY) to create a sharp border of the landscape in the map. *coni4* (Appendix 2.3: Map E) was created as an input map with GIS procedures to be used in the FRAGSTATS software.

2.5.3 Quantifying patch shape

The FRAGSTATS output map of the conifer plantation in the study area was given a patch identification number and combined the factors on a patch-by-patch and later pixel-by-pixel basis. The perimeter of every patch (with raster analysis: illustrated in Figure 2.3.1a) was calculated using GIS (PERIM) and compared the area was with a circle of the same patch perimeter length (SCALAR).

The model assumed that a truly circular shape of patch could resist the wind at a maximum level because of its reduced edge effects. However, when it deviates from the circular shape then the resistance from the patch will be less. It may create some pockets, which may increase the funnelling effect of wind and decrease the resistance. The effects of patch shape to windiness were quantified in different proportions (15%, 20%, 25% increase of DAMS).

The maps were analysed and presented with the data with a view to demonstrating the user-defined mode and accommodating techniques (patch shape quantifying by FRAGSTAT) within GIS framework. Burrough and McDonnell (1998) also supported the idea that GIS has the potential to sort and rearrange data according to user demand.

2.5.4 Quantifying soil classes

Soil classes were quantified with respect to soil score using the Boolean operator (RECLASS), image cross-tabulation (CROSSTAB), arithmetic progression (SCALAR), and addition of maps (OVERLAY).

Cross tabulation (CROSSTAB) was facilitated to identify the soil classes of the conifer plantations in the study area. The Boolean maps (RECLASS) were created to classify the soils according to their tabulated score in Appendix 2.5, such as: brown earth, brown alluvial, podzols, brown podzolic, humic brown podzolic were given a score of 1.00 (Appendix 2.5). These soil classes were separated from other soil classes of the study area and all were placed in single map *recouts1* (Appendix 2.3: Map J) with a value 1. This grouping of soil classes leads to quantification of the soil class with the arithmetic operator of GIS (SCALAR). GIS also added all the maps (OVERLAY) with a specific soil score and finally created four maps with 25%, 20%, 15% and 10% increase of DAMS as contributions.

2.5.5 Quantifying leaf presence

This study identifies leaf presence in winter as a potential additional factor other than patch shape to weight DAMS. In WCM an addition with the DAMS value (1% increase of DAMS score) was needed to combine the leaf presence in winter to choose a windiest area. The arithmetic operator of GIS (SCALAR) was applied to quantify leaf presence in winter. The value for presence of leaf was straight forward. However, there is no effect of differentiation among the four combination scenarios for leaf contributions as conifer plantations of the Snowdonia National Park (SNP) are considered as the study area.

2.5.6 Combining of factors

Eventually, all the desired information of the contributions of patch shape, soil classes and leaf presence were put together with DAMS data set to create final maps with respect to the four combination scenarios using OVERLAY function of GIS.

2.5.7 MACRO statements

The percentage contribution of different factors (choice of scaling) may be changed for different situations. New variables may be added or replaced with the availability of authentic research results in the future. The macro language has the capability to accommodate the results by replacing the languages that create the maps. This accommodative nature makes the IDRISI GIS and GIS modelling in general, very useful.

Furthermore, macro statements about all the GIS procedures enable any forest manager to change the management options at any stage of planning. Therefore, when top management requires any change in planning, GIS can visualise the change and foresee the after effects very quickly. The four scenarios of WCM model required less than one hour to create 140 maps with an Intel Pentium III computer of 600 MHz, 64Mb RAM. It is also very helpful to detect and amend errors, in the process of map preparation, through macro operator of GIS.

2.5.8 Improvements in wind-risk modelling

The Forestry Commission developed ForestGALES, software using DAMS to quantify the wind-risk of any forest based on measured or predicted stand characteristics (Forestry Commission, 2000; Gardiner and Quine, 2000). This software did not incorporate the patch shape and leaf effect of existing forests but is a comprehensive tool to demonstrate the wind hazard possibility for plantation species of the United Kingdom. Gardiner *et al.* (2000) compared the model ForestGALES (UK model) and HWIND (a Finnish wind–risk model) to verify field data for the critical wind speed to uproot and break coniferous trees and concluded that the small differences in their predictions in critical wind speed led to large differences in estimates of damage and required an improved prediction. Incorporation of patch shape and leaf as additional potential factors with proper weighting in this study may improve the prediction of wind-risk assessment.

2.5.9 Impacts of WCM model in the study area

Selection of land between windiest to less windy

The Snowdonia National Park Authority (SNPA) is committed to the creation of new native woodland and looking for land located in the study area. The Forestry Authority of Wales and the Snowdonia National Park management decided to increase the native woodland in Wales by an average of 58 hectares per year for the next 20 years (SNPA, 1995). Furthermore, the Forestry Commission also made an agreement with the Snowdonia National Park Authority (SNPA) to find the land to create new native woodland. Four combination scenarios of wind composite model (WCM) create the scope to identify areas that may be used to create native woodland. Table 2.4.1 illustrates the land available for use other than conifer, in the conifer plantations of the Snowdonia National Park (SNP). Lands were identified with target of 1160 hectares of the SNPA in a descending order from highest WCM score (expressing the windiest areas) to lowest. 1341 hectares, 1520 hectares, 1358 hectares and 1212 hectares of land may be *too windy* for commercial plantations and may have potential for native woodland with four combination scenarios WCM1, WCM2, WCM3 and WCM4 respectively.

Selection of land over the limit of suitability of WCM for Sitka spruce

Table 2.4.3 illustrated the lands which are located over the limits of suitability of four scenarios of WCM for Sitka spruce. 1288 hectares, 1246 hectares, 924 hectares and 626 hectares of land may be potential for native woodland with four combination scenarios WCM1, WCM2, WCM3 and WCM4 respectively. Although these limits of suitability also apply to native broadleaved woodland species (as DAMS score 22 is unsuitable for native woodland species), this is a limit for the growth of commercial utilisable timber (Hale *et al.* 1998). Native broadleaved species will grow on these windy sites in a scrubby forest which may adequate for conservation objectives.

2.5.10 WCM: an example of application of spatial data management

A. *Patch shape estimation in windiness scale*

The WCM has attempted to calculate the patch shape with GIS and FRAGSTAT. GIS techniques have made it possible to integrate the patch shape contribution with windiness scales. Every patch of Sitka spruce in the study area was identified and their contributions were combined with the DAMS score to produce WCM.

B. *Integrating management option, local problem, prospects and technology*

The GIS procedures followed in four combination scenarios of WCM demonstrated an automated process of decision-making about forest management where wind was treated as a hazardous factor of management. The WCM also incorporated management options for conifer plantations to highlight the areas that may be *too windy* for the plantation and may be potential for the creation of native woodland considering conservation strategies of native species. Any modification with a user-defined option can be altered with the change of macro texts of the programme, offering its flexibility. Following figure illustrates GIS contribution in an integrated manner.

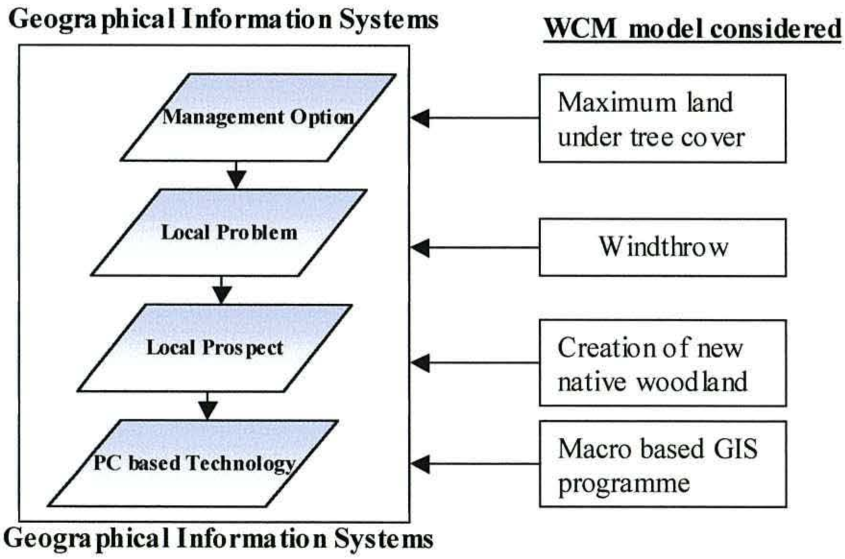


Figure 2.5.1 GIS based approach in WCM model in the study area.

2.5.11 Limitations of wind composite model (WCM)

Wind composite model for the case study was not validated by field observations. The land use data regarding the study area were from early 1990, so any harvested or newly planted areas in the study sites were not included. Seasonal variation of wind flow is another factor for the validation of the DAMS data set. WCM only estimated the patch area up to 0.25 hectare. Some vital factors such as patch orientation and patch edge: area ratios were not included in the model. They need further study which may lead to better estimation. Therefore, it is not wise to use the WCM in its present form as a firm policy or management tool because validation of results on the performance of the models has not yet been done. The proposed methodology, to apply GIS for integrating spatial data sets and techniques may be treated as an example of analysis of the components contributing to windiness as a general model: WCM.

2.5.12 Steps for validation (Proposal)

Validation of the combinations (WCM) may be possible if data sets of actual wind damage for Snowdonia become available for study. Then the area with the different WCM score zones (from 14 to upward) may be created. Sample plots may be chosen from the WCM score zone areas to estimate and verify the real patch shapes, orientations and soil classes. Quine and Bell (1998) used wider windthrow monitoring of eight forest areas in upland Britain, and Quine (2000) carried a validation process for mean wind climate to predict wind risk assessment. These studies may be a good guide for the validation process of the present study. Patches may be selected from elongated to nearly circular shape and wind speed verification may be prescribed with respect to different shaped patches. Similar experiments may be conducted for deciduous species to see the leaf effect. Then the factor relationships may be established with the actual hazard with respect to WCM zone.

2.6 Summary of the chapter

A geographical information system is proposed as a suitable tool for modelling the interaction between wind and forest areas. Using the forest area of the Snowdonia National Park in North Wales, UK, (affected by endemic windthrow) as the study area, land use, soil, windiness data set (DAMS) of the Forestry Commission of Great Britain were incorporated within a GIS. Shapes of forest patches were estimated through FRAGSTATS and placed in a GIS to combine the patch shape contribution with windiness. Four combination scenarios were generated from the contributions of patch shape, soil class and leaf presence in winter, combined with DAMS. This enabled a study of high wind risk areas. It was not possible to identify which combination was the best because all combinations need proper validation with field-based study on a very local scale.

GIS was used to demonstrate how various factors contributing to windblow could be combined. It was also possible to show the *too windy* areas could be mapped, and perhaps chosen for conversion to native woodlands.

CHAPTER THREE
CARBON SEQUESTRATION

3.1 Introduction

3.1.1 Carbon sequestration: an issue to consider in forest management

The objective of this chapter was to develop a methodology to analyse the role of spatial data and GIS in planning and modelling of woodland considering a topical issue - carbon sequestration. To act in accordance with the main objective, the following specific objectives (Figure 3.1.1 shows the flow towards main objective) were set:

- to produce a GIS model to estimate tree and litter carbon stocks using species and yield class;
- to develop a GIS model to estimate the organic carbon stock of woodland soil considering its type and layers (up to 1 metre depth);
- to develop a GIS procedure to compare the carbon sequestration consequences of replacing exotic conifer plantations with native broadleaved woodlands. Three scenarios are considered, based on stand productivity.

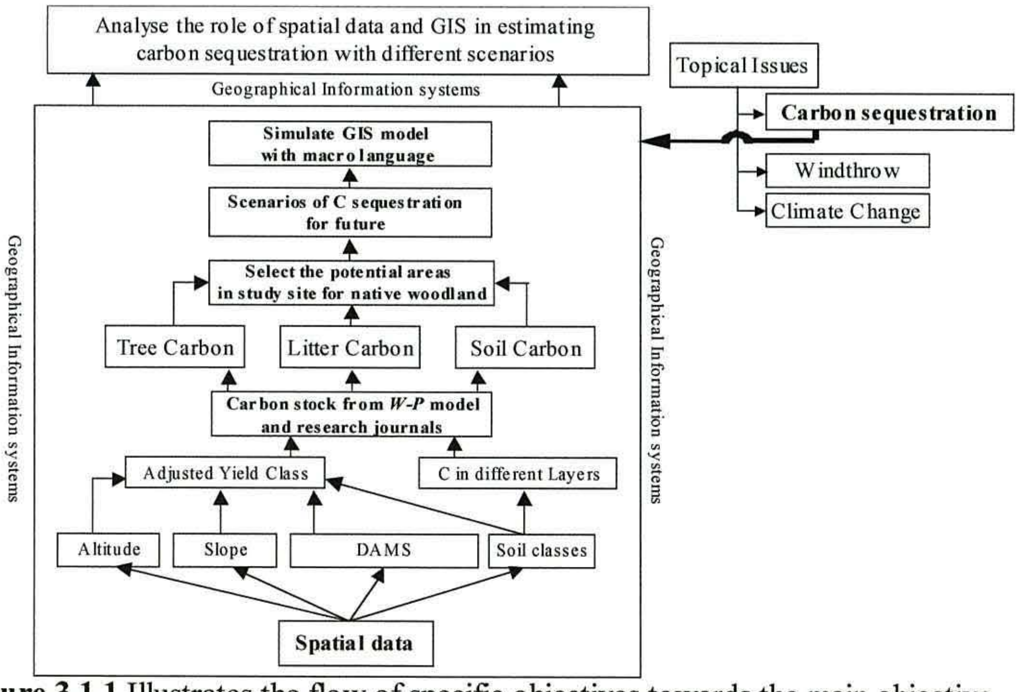


Figure 3.1.1 Illustrates the flow of specific objectives towards the main objective for any species.

3.1.2 Background and rationale of study

Science

The atmospheric accumulation of carbon dioxide (CO_2) is the balance between fossil fuel combustions and land-use change emissions and the uptake due to oceanic and terrestrial sinks (Watson *et al.*, 1992). CO_2 is removed from the atmosphere by a number of processes that operate on different time scales, and is subsequently transferred to various reservoirs, some eventually returning to the atmosphere. For CO_2, the fastest process is uptake into vegetation and the surface layer of the oceans, which occurs over a few years. Various other sinks operate on the century time-scale (*e.g.*, transfer to soils and to the deep ocean) and so have a less immediate effect on the atmospheric concentration. Within 30 years about 40%-60% of the CO_2 currently released to the atmosphere is removed. However, if the emissions were reduced, the CO_2 in the vegetation and ocean surface water would soon equilibrate with that in the atmosphere, and the rate of removal would then be determined by a slower response of woody vegetation, soils, and a transfer into deeper layers of the ocean (Houghton *et al.*, 1998). Moreover, the mitigation of CO_2 has also been focused by several researchers (Penman, 1996; Fearnside, 1995; Kokorin *et al.*, 1996; Cairns and Meganck, 1994). The accumulation of greenhouse gases in the atmosphere, particularly CO_2, is projected to alter the earth's climate (Schroeder *et al.* 1993).

Forest management

The potential role of forests in carbon sequestration has been evaluated by a number of researchers. Johnson and Sharpe (1982) stated that forests become net sources of carbon when biomass is reduced by deforestation, harvest or fire leading to a net release of carbon to the atmosphere. Once more, forests are carbon sinks when reforestation and growth remove carbon from the atmosphere on a net basis and store it as biomass and detritus. Forest systems cover more than 4.1 x 10^9 hectares of the earth's land area. Globally, forest vegetation and soils contain about 1146 gigatonnes (10^9 tonne = 1 gigatonne) of carbon, with approximately 37% of the carbon in low-latitude forests, 14% in mid latitudes and 49% at high latitude (Dixon *et al.*, 1994). Kokorin and Nazarov (1995) also illustrate that forests and their soils are giant reservoirs of carbon and specially referred to the boreal forests of Russia, where forests contain more than 250 gigatonnes of carbon which is 400 times more than the national annual CO_2 anthropogenic emission *i.e.* 0.65 gigatonnes Cyr^{-1}. Landsberg and Gower (1997) have indicated that the forest canopies are an important component of surface control on climate from very local to global scales. The authors also point out that forests are a significant component of the global carbon balance. According to IPCC (1996), mature forests are a large terrestrial store of carbon. Deforestation, which is already causing a net release of carbon from tropical lands to the atmosphere of 1.6 (± 1.0) gigatonnes C yr^{-1}, may increase to meet the food needs of an expanding human population, and extensive deforestation could adversely affect the biosphere's continued capacity to act as a carbon sink. Further uncertainties arise because changes in climate and atmospheric CO_2 over the next decades to a century are likely to produce changes in the structure of natural and managed ecosystem.

As a management consideration, the need to predict the carbon balance of stands along with the pattern of allocation of the carbon remains a central problem. While a manager is concerned with the stand productivity or the carbon balance of ecosystems, a policy maker, politician, or bureaucrat is concerned with carbon fixation by forests and prediction of the global carbon balance (Landsberg and Gower, 1997). Forest management for wood production is essentially a matter of manipulating stands to optimise the harvestable yield, which entails maximising the production of carbon and its allocation to useful products *i.e.* tree stems (Landsberg and Gower, 1997).

These statements lead a forest manager to count carbon as an important criterion for forest management systems. Moreover, CO_2 acts as a vital decisive factor and a yardstick of climate change from the local to global scale.

3.1.3 Developing the organic carbon model for woodland

If a forest manager expresses carbon content as a total output of woodland then it:

- may be able to give a clear scenario of how much above and below ground organic carbon is retained, which may facilitate lesser degree of uncertainty of missing carbon sink and help the legislator to prepare a national network for carbon.
- may provide the same yardstick for valuing climate change scenarios with other related factors.
- may be capable of accounting for the whole biomass of forest trees, soil resources and their interactions.
- may offer a chance for the forest to standardise with globally accepted parameters of measurement.
- may provide a useful standard to evaluate the contribution of land use changes such as from conifer plantation to native woodland.

However, it is required to estimate how much carbon is in a single reservoir and how much annual increment can be removed in relation to global, regional and eventually local perspectives. Again, Pollard (1991) pointed out that foresters should prepare themselves with sound quantitative information that will challenge the validity of ambitious and perhaps inappropriate schemes for storing carbon, foresters may then well find themselves on the positive side of the carbon balance. Nevertheless, the questions remain:

- how the sequestered carbon will be estimated for each species and yield class.
- how the land use change will be predicted if any forests will be converted into other land use in the future.
- how the available spatial database can provide the sound, quantitative information about carbon to see the differences between land use changes.

These questions dictate that a need exists to develop a theoretical framework and a model and the forest manager would be required to use the available spatial datasets for woodland for its management and reorganisation. This study will present a model to estimate carbon content of woodland and will also show the consequences if the landuse changes (three scenarios are presented to show how high the yield class 2, 4 and 6 of oak would be in order to fix as great a carbon stock as the conifer) in the Snowdonia National Park (study area), considering the spatial datasets with the available information and expert advice. Figure 3.1.2 portrays the spatial datasets used to construct the organic carbon model.

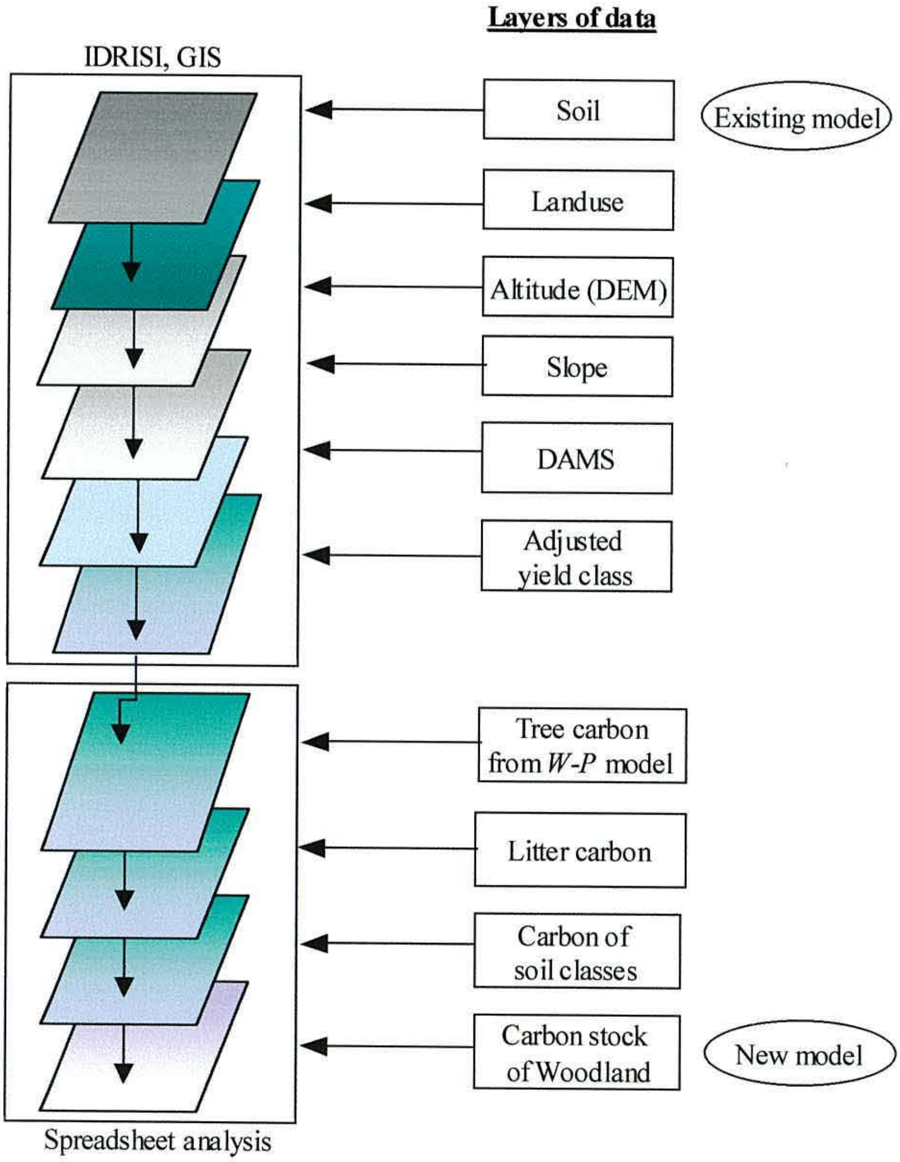


Figure 3.1.2 Viewing procedure to construct an organic carbon model for woodland using GIS.

3.2 Literature review

This part presents: the review of literature regarding global concern over carbon sequestration, missing carbon sinks, yield classes and GIS incorporation, models generated to estimate forest carbon, carbon reserves of the United Kingdom and effects of forest management and land use changes on carbon sequestration.

3.2.1 Global perspective

The contribution of CO_2 in global warming has been studied by a number of authors (Melillo *et al.*, 1993; Cooper, 1982; Liang *et al.*, 1996). It became a challenge for human beings (Watson *et al.*, 1992) to reduce the existing level of CO_2 (Penman, 1996; Fearnside, 1995; Kokorin *et al.*, 1996). Carbon sequestration takes place in two major ways: oceanic sequestration and terrestrial sequestration (Johnson and Sharpe, 1982; Price, 1997) and is described in different carbon cycles (Cooper, 1982; Detwiler and Hall, 1988). The forest ecosystem contains a single large pool (1146 gigatonnes; Dixon *et al.*, 1994) of carbon as terrestrial biota in the global carbon cycle, while the ocean is the largest sink of the carbon (Francy *et al.* 1995; Pollard, 1991; Cannell and Dewar, 1995).

Clement *et al.* (2000) pointed out that the forest, an interface between the atmosphere and the soil, transfers carbon from atmosphere to soil. It was estimated that forest vegetation and soil carbon pool are about 340 gigatonnes and 620 gigatonnes respectively, while most vegetation of the carbon pool (62%) is located in low-latitude forests, and the soil carbon pool is largely found in high latitude forests (54%) (Brown *et al.*, 1996). On the other hand, Dixon *et al.* (1994) estimated that the forest vegetation and soils contain 359 gigatonnes and 787 gigatonnes of carbon respectively, and a large part of the vegetation (25%) and soils (59%) of carbon pools, is located in high latitudes (more than mid and low latitude). Several authors specifically studied the tropical terrestrial carbon sinks (Cairns and Meganck, 1994; Chiba, 1998; Watson *et al.*, 1992) and the temperate terrestrial carbon sinks (Penman, 1996; Singh and Wheaton, 1991; Cannell, 1996).

3.2.2 Missing carbon sink

A better understanding of carbon estimation is needed to reduce the discrepancy about the 'missing' carbon. Several scientists approached the 'missing carbon' (Detwiler and Hall, 1988; Gifford, 1994). As Gifford (1994) indicated, the missing sink of carbon in the global carbon cycle is about 0.4 to 4.0 gigatonnes. A number of researchers also studied missing carbon and the pricing and valuation of carbon (Price and Willis, 1993; Price, 1994; Price, 1995; Reddy and Price, 1999; Hoen and Solberg, 1994; Price, 1997). Reddy and Price (1999) presented the total carbon accumulations in closed forests of South and Southeast Asian countries. Thornley *et al.* (1991) reported that the reasons behind the missing sink were CO_2 and nitrogen fertilizations of terrestrial ecosystem from pre-industrial times and also calculated that the missing sink accounts for about 70 gigatonnes of carbon.

3.2.3 Carbon reserve of the United Kingdom

The largest and second largest natural (stores in biomass and soil) carbon reservoirs in the UK are the organic matter in peat soil (3 gigatonnes) excluding lowland fens and the forest and woodland (0.092 gigatonnes of carbon, which represents 80% carbon in all vegetation) (Cannell *et al.* 1993; Cannell and Dewar, 1995). Cannell (1999a) showed a contrasting scenario regarding the total emission and sequestration of carbon for the UK.

Cannell *et al.* (1996) reported the carbon sequestered in the forests of Northern Ireland (total 78300 hectares) and estimated average sequestered carbon was 2.20 to 2.90 tonne per hectare per year. The national inventories of terrestrial carbon sources and sinks for the UK was conducted by Cannell *et al.* (1999). This document adopted the methodology of expression of carbon sink (-) and source (+) of the United Nations Framework Convention on Climate Change (UN-FCCC). Table 3.2.1 illustrates the carbon sources and sinks of the United Kingdom.

Table 3.2.1. Estimated terrestrial CO_2 carbon sources and sinks in the UK in 1990 (Cannell *et al.*, 1999) (updated from million tonne to gigatonnes).

Sinks	Gigatonnes / yr	Sources	Gigatonnes / yr
Forest biomass and litter	(-) 0.0021 (±15%)	Cultivation	(+) 0.0062 (±50%)
UK forest products*	(-) 0.0005 (±25%)	Urbanization	(+) 0.0016 (±50%)
Non forest biomass	(-) 0.0003 (±30%)	Drained peat lands	(+) 0.0003 (±30%)
Forest soils	(-) 0.0001 (±30%)	Drained fen lands	(+) 0.0005 (±20%)
Set-aside soils	(-) 0.0004 (±50%)	Peat extraction	(+) 0.0002 (±20%)
Undrained peatlands	(-) 0.0007 (±40%)	Export to sea	(+) 0.0014 (±30%)
Salt marshes	(-) 0.0001 (±20%)		
CO_2 and N fertilization	(-) 0.0020 (±60%)		
Total	(-) 0.0062		(+) 0.0102

* Change in forest and other woody biomass stocks.

3.2.4 Yield class prediction and GIS modelling

To date, no studies have been published on predicting yield classes of the forests of Wales, UK using GIS except Bateman and Lovett (1998). Bateman and Lovett (1998) presented a model using IDRISI GIS (Eastman, 1993) to predict the yield classes considering accumulated temperature, rainfall, water available, moisture deficit, field capacity, workability and soil type. However, Macmillan (1991) considered elevation, topex, soil moisture status, aspect and soil classes as criteria to predict the yield classes for Sitka spruce. A small number of researchers judged elevation, temperature and soil types with site factors (geomorphic shelter-topex, aspect, soil depth and rooting ability) to predict the general yield class for Northern Britain (Worrell, 1987; Worrell and Malcolm, 1990a; Worrell and Malcolm, 1990b; Tyler *et al.*, 1996).

Busby (1974) suggested a yield guide for upland Britain. Furthermore, the study specified the yield class determining factors such as exposure, altitude and soil class, and also specified the rotation according to elevation and terrain position. However, Macmillan (1991) pointed out that the Busby (1974) guidelines underestimated the general yield class estimation. Pyatt (1977) explained the relationship between the yield classes and the site types with their soil characteristics.

3.2.5 Models for carbon storage in tree, litter and soil

3.2.5.1 Carbon models

Dewar (1991) presented the most prominent analytical models of carbon storage in the trees, soils and wood products of managed forests for the UK. Dewar and Cannell (1992) also generated a carbon flow model to estimate carbon for forest plantations of the UK and estimated that 2 to 5 tonnes of carbon per hectare per year was stored by most of the plantations. Cannell and Dewar (1995) developed the Dewar (1991) model and specified the carbon contents for stem, litter and soil with respect to forest types and species. Thornley and Cannell (1996) presented a carbon model that examined forest growth in relation to the IS92a scenario (details in Table 4.2.1) of climate change. Cannell *et al.* (1999) used the same models to estimate carbon reserves for the UK. Chiba (1998) developed a carbon model which described five carbon stocks: atmosphere, foliage, woody matter, underground matter and dead organic matter in the soil for man-made forests in Japan. In addition, the study focused on litter carbon and natural disturbances like windthrow, which contributes a substantial amount of litter carbon in a forest.

Kokorin and Nazarov (1995) conceived a carbon model for estimating the climate-induced change in carbon balances for the forests of Russia. Pinard (1995) estimated carbon from the total biomass including trees, understory and roots and compared reduced impact logging (RIL) to conventional impact logging for the tropical trees of Malaysia. Hoen and Solberg (1994) developed a model for the estimation of carbon emissions from forests considering biomass and growth patterns of the species of the forest. Furthermore, the study analysed the contribution of silvicultural practices as a management option with an economic valuation of sequestered and emitted carbon.

Bateman and Lovett (2000) presented models of carbon storage for hardwood and softwood and forest soils with a case study in Wales, UK. Moreover, these models were applied to the conifer species, Sitka spruce (*Picea sitchensis*) and a broadleaf species, beech (*Fagus sylvatica*). The study used yield classes of species to determine the biomass and eventually calculated the carbon content and turned it into an economic valuation. Cannell and Dewar (1995) estimated carbon contents of UK plantations assuming all conifer trees were *P. sitchensis* with yield class 14. In addition, the study suggested the planting of conifers would need to be continued.

3.2.5.2 Litter carbon

Litter carbon has a significant contribution to soil organic matter (Dewar, 1991; Cannell and Dewar, 1995; Harrison and Harkness, 1993). Dewar and Cannell (1992) estimated the litter carbon taking into account the foliage, fine roots, branches and woody roots as input and used fractional decomposition rates in accordance to species. Data regarding litter carbon were extracted from this research paper to calculate the litter carbon stock for the study area (details in section: 3.3.2.2).

Forest litter carbon and its contribution to the soil carbon pool along climate variables, temperature and precipitation, was investigated by Simmons *et al.* (1996) and it was suggested that precipitation had a significant effect on the litter carbon pool. Harrison and Harkness (1993) also studied the litter carbon of Meathop Wood (a mixed deciduous oak/ ash/ birch woodland) and presented an estimate of organic carbon considering leaf, branches and twigs (Table 3.2.2)

Table 3.2.2 Estimated carbon inputs as litter components for Meathop Wood. (Adapted from Harrison and Harkness, 1993).

Litter component	Carbon input (tonne/ha)
Tree and shrub leaf	1.620
Branches and twigs*	0.640
Flowers and fruits	0.080
Herb layer	0.330
Through fall and stemflow	0.230
Root decay	0.995
Total	**3.895**

* Branch material = 10-50 mm diameter and twig material = 2-10 mm diameter.

3.2.5.3 Soil carbon

Carlyle (1993) estimated the carbon contents of sandy soil from 0 to 100 cm depth and found a higher concentration of carbon was present in 0 to 16 cm depth than other layers. Carbon sequestration will be changed with climate change, more specifically with elevated ambient CO_2 scenarios (Niklaus *et al.*, 2000; Monreal *et al.*, 1997; White *et al.*, 2000).

Ten selected forest types were examined by Naburs and Mohren (1995) for carbon reserves and estimated carbon content was considered with respect to mean stem volume increment, carbon turnover rates of tree organs: foliage, branches and roots, and also turnover of stable humus up to 100 cm depth of soil. Rudeforth *et al.* (1984) presented a broad range of soil studies for Wales, UK, which is a major basis on which soil carbon was calculated in the study area. Owens *et al.* (1999) estimated mineral soil carbon content using the following equation:

$$\text{gmC} = \text{Area (ha)} \times (10000\ \text{cm}^2 / \text{m}^2) \times (10000 / \text{ha}) \times \text{depth of soil (cm)} \times \text{Bulk density} \times \%\text{C}.$$

where, area is equivalent to the area of soils, soil depth refers to the range of depth being examined and bulk density is the apparent density of the soil, as it exists in the field at the time of sampling (Avery, 1990).

Harrison and Harkness (1993) studied the gross annual turnover rate of soil carbon within the tree rooting zone (0 to 50 cm depth) of a mixed deciduous oak/ ash/ birch woodland (Meathop Wood) situated on an acid brown earth soil overlying carboniferous limestone. Table 3.2.3 illustrates the carbon contents of Meathop Wood with the depth of soil layers and mean residence time.

Table 3.2.3 Estimated carbon content, mean residence times (MRT), and annual carbon flux from the rooting zone of the Meathop Wood soil profile. (Harrison and Harkness, 1993)

Depth (cm)	**Carbon Content (tonne/ha)**	**Mean Residence Time (year)**	**Carbon Flux (tonne/ha/yr)**
$0 + 0_f$	4.650	2	2.325
0-5	18.030	18	1.001
5-10	14.200	40	0.355
10-15	11.990	100	0.120
15-25	15.270	500	0.030
25-35	10.100	600	0.017
35-50	7.280	600	0.012
Total			**3.860**

Laine and Minkkinen (1996) examined the drainage of soil carbon and its effects on the total organic carbon estimate. In contrast, Hollinger *et al.* (1993) ignored the carbon storage in mineral soils and suggested that there was little change in forest soil carbon storage over a rotation. Johnson (1993) pointed out that coordinated research is needed to estimate soil carbon with a view to climate change and its effects on forest management.

3.2.6 Land use change and carbon sequestration

Terrestrial carbon sequestration is openly related with land use system. Deforestation can make a sink a source of carbon, many tropical forests are exploited by people for their day to day living (Houghton, 1991; FAO 1981; Flint and Richards, 1991). Harmon *et al.* (1990) pointed out that conversion from old–growth to young forest maximised carbon sequestration. Dewar (1991) developed a model to calculate and compare the carbon sequestration in old–growth and young forest. Dale *et al.* (1991) estimated the effects of landuse change on carbon storage and concentration on a global scale. Furthermore, Hall and Uhlig (1991) estimated carbon released from tropical land use change. Both pieces of research indicated that the prominent causal factors for land use change in the tropics are agriculture and urbanization, while Hall and Uhlig (1991) pointed out that biomass estimation procedures act as a major factor to calculate the amount of carbon. Owens *et al.* (1999) pointed out that the most influential cause of the drop of soil carbon content at landscape level was the shift in land use, and therefore land cover types. Dewar and Cannell (1991) suggested that in the long-term (100 years) broadleaved plantations of oak and beech store more carbon than conifer.

3.2.7 Forest management

The potential role of forests to sequester carbon has been assessed by a number of researchers (Schroeder *et al.*, 1993; Jhonsen *et al.* (2001); Winjum *et al.*, 1993; Solberg, 1994). Cannell *et al.* (1993) studied carbon storage by *P. sitchensis* (yield class 12) on peat lands in Britain and estimated 167 tonnes per hectare accumulated which is equivalent to the carbon stored in about 35.5 cm deep peat soil or 20.9 cm of shallow peat. The study concluded that if conifers are planted on peat soil substantially deeper than 35.5 cm, in deeper peat or 20.9 cm in shallow peat, in the long run there could be a loss of CO_2 carbon. Healey *et al.* (2000) reported that the reduced impact logging (RIL) method was an option of forest management to reduce carbon emission. Cannell (1999b) illustrated carbon conservation through forest management considering climate change scenarios. Carlyle (1993) pointed out that weed control as a management option in forests reduced carbon sequestration. Harrison and Harkness (1993) investigated the effects of birch on carbon dynamics in acidic heather moorland soils and concluded that birch woodland has shown an increase of earthworm numbers, pH and extractable calcium, and mineralisable nitrogen; and a significant decrease of the C: N, C: P, and C: K ratios in surface soil. However, the study mentioned that the rate would depend on the contribution of organic matter decomposition and the biological activity of microbes.

3.3 Materials and Methods

This part introduces the model considered for carbon sequestration, including the details of data and maps used in the model in a case study. The methodology adopted to run the model, validate it and to demonstrate the methods considered for observing the change when replacing conifer species with broadleaf species with three scenarios using GIS, is also presented.

3.3.1 Model

The following empirical organic carbon model used to estimate carbon sequestered for any species in woodland using GIS.

$T_{OC} = (Tr_C + Li_C + So_C) \times A$................................Model 1

where, T_{OC} = Total organic carbon, Tr_C = Tree carbon stock, Li_C = Litter carbon stock, So_C = Soil organic carbon stock up to 1 metre depth, A = Area.

The following models were developed to estimate Tr_{CF}, So_{CF} and Li_{CF}:

$Tr_C = (AYC \times C_m)$

$= [\{YC_s + E_{(j\,k\,l)}\} \times C_m]$..................................Model 1a

where, AYC = Adjusted yield class, C_m = Carbon stock from Willis-Price (*W-P*) carbon model (Price, 2001, pers. comm.), YC_s = Yield classes of Pyatt (1977) and expert advice, $E_{j\,k\,l}$ = Adjustment effects of $_j$ = altitude, $_k$ = slope, $_l$ = exposure to wind.

$Li_C = AYC \times Li_{cs}$..Model 1b

where, Li_{cs} = Litter carbon stock with respect to yield classes (extracted from Dewar and Cannell, 1992).

$So_C = (LOC)_{O\,A\,B\,C} \times (TLO_{CS} / MOC_{TL})$...............................Model 1c

where, LOC = Total organic carbon stock in soil layers ($_{O,\,A,\,B,\,C}$) of soil classes in the study area, $_O$ = 0 to 3 cm depth, $_A$ = 4 to 14 cm depth, $_B$ = 15 to 30 cm depth, $_C$ = 31 to 100 cm depth, TLO_{CS} = Tree and litter carbon stock per hectare for a given species and yield class, MOC_{TL} = Mean of tree and litter carbon stock per hectare for all yield classes concerned.

Finally, Model 1 stands in the following way for any species in woodland:

$T_{OC}=[\{(YC_s+E_{j\,k\,l}) \times C_m\}+ (AYC \times Li_{cs})+\{(LOC)_{O\,A\,B\,C} \times (TLO_{CS} / MOC_{TL})\}] \times A$

The following figures elucidates the flow of components and illustrates how organic carbon model was developed:

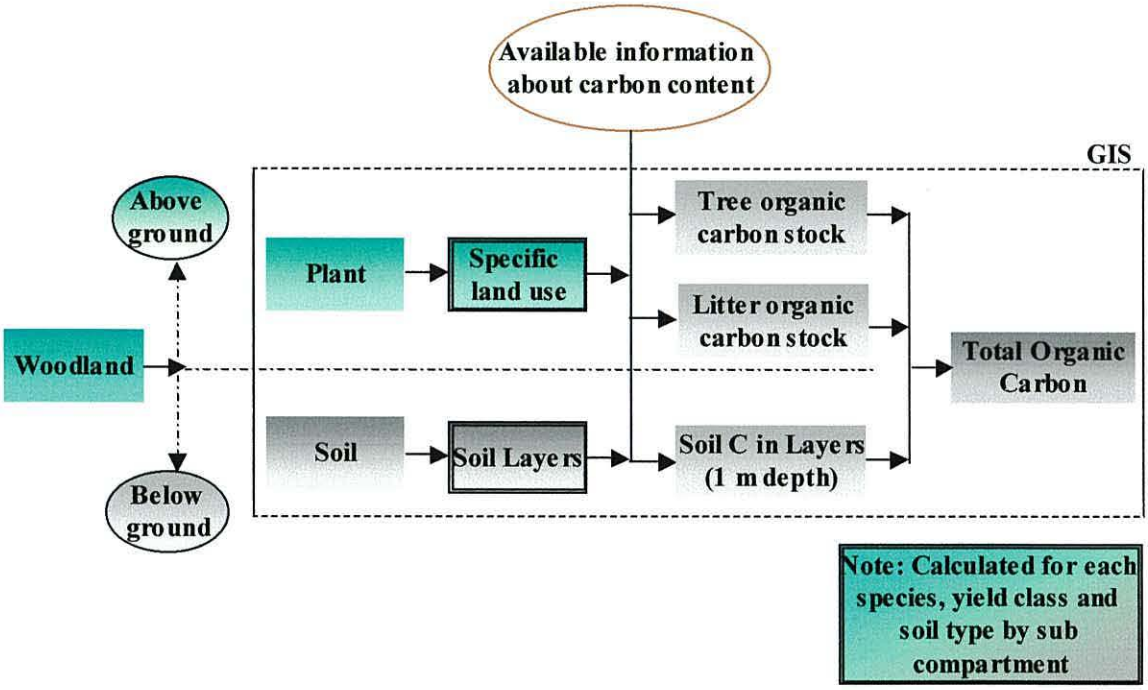


Figure 3.3.1 Flow demonstrating the estimation of total organic carbon (T_{OC}) sequestration for any species in woodland.

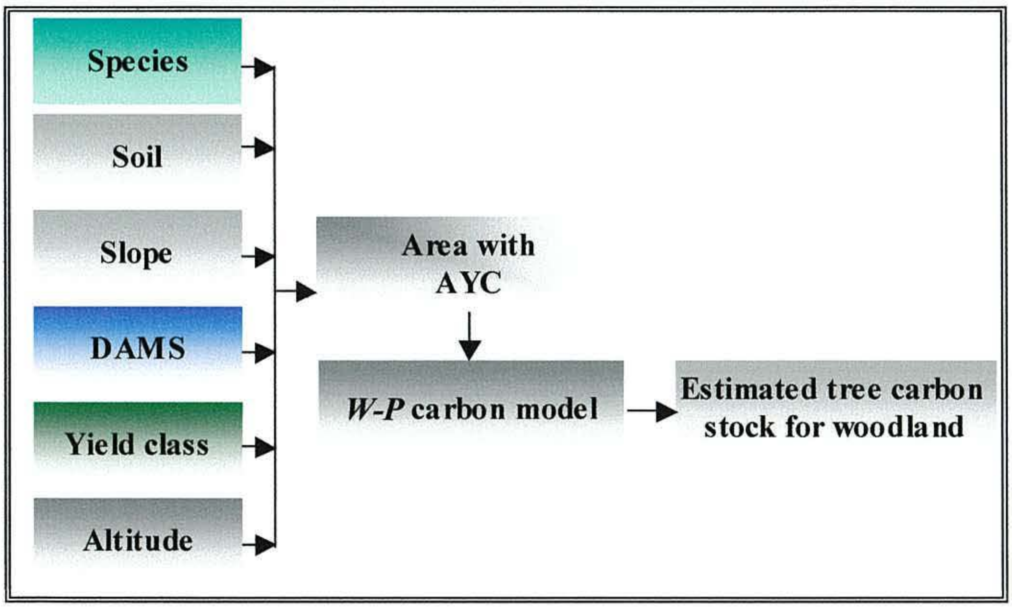


Figure 3.3.2 Illustrating the estimation procedure of tree carbon stock for woodland (AYC = Adjusted yield class and *W-P* = Willis –Price model).

3.3.1.1 A case study: Application of the model in the study area

The model was applied to develop a GIS procedure to compare carbon sequestration consequences of replacing exotic conifer plantations with native broadleaved woodland using three scenarios in the study area. The Snowdonia National Park was selected as the study area. Details of the study area including its geology, soil, climate, land uses and ownership were described in chapter 2 of section 2.3.3.1.

3.3.1.2 Data sources

Four main sources were used to collect data. The Forestry Commission (supplied data of **D**etailed **A**spect **M**ethod of **S**coring), the Centre for Ecology and Hydrology (CEH), published research journals and the School of Agricultural and Forest Sciences, University of Wales, Bangor, UK (SAFS, UWB). DAMS description, workability and CEH maps were described in chapter 2 of section 2.3.3.2.

Published books, Journals and expert advice

Data in relation to soil carbon is a scarce resource for the study area (Snowdonia National Park). Data about litter carbon stock with respect to yield class were extracted from Dewar and Cannell (1992). Data of soil classes, soil organic carbon presence (in percentage) and bulk density with respect to its depth, for the study area were extracted from Rudeforth *et al.* (1984), Avery (1980) and the Soil Survey of England and Wales (1983). Where the carbon presence percentage and bulk density were not available, local expert advice was taken.

Data from the School of Agricultural and Forest Sciences (SAFS, UWB)

The IDRISI GIS database containing land-use, elevation, slope, aspect, and soil type data sets (at 40m x 40m resolution) for the Snowdonia National Park were available on the network of the School of Agriculture and Forest Sciences.

Following are the specifications of the maps used in this study from SAFS, UWB.

Table 3.3.1 Data collected from SAFS, UWB for the study.

Name	Data type	Parameter	Class width	Note
snplu80	RASTER	Land use	_	CC / Silsoe college mid 1980s survey, ground and aerial photography
snp5con	RASTER	Elevation	5 metre DEM	Altitude (Digital elevation Model)
snpslp	RASTER	Topographic Slope	5^0	Slope in degrees (^{0}), calculated from DEM.
snpasp	RASTER	Topographic Aspect	45^0	Compass direction, 0^0 to 360^0
snpsoilt	RASTER	Soil type	_	Soil classes
snpbound	VECTOR	_	_	SNP boundary

3.3.1.3 Tools used in the study

Geographical Information Systems: IDRISI

The main platform for the study was the IDRISI for windows version 2.0, GIS software.

Willis - Price (W-P) Carbon Model

A computer automated Willis - Price (*W-P*) carbon model (Price, 2001, pers. comm.) was used to calculate carbon stock with respect to yield class of selected species. This is a Quattro-Pro, DOS-based computer programme. This programme enables the estimation of the tree organic carbon stock for species, with its rotation considering live and dead wood components (biomass- comprises harvested wood, sawn wood, panels, papers, mining and other waste products).

Minitab 13 and Spreadsheet packages

All the statistical analysis for the study was done with Minitab 13. Spreadsheet packages: Excel 2000 and Quattro-Pro 8 were used to organise the data and to construct the charts.

3.3.2.Methods

The study considered *Picea sitchensis,* as a conifer species and assumed the entire conifer plantation is the plantation of *Picea sitchensis* in the study area.

3.3.2.1. Estimation of tree carbon

Tree organic carbon was estimated with respect to yield class of the species (with maximum annual mean increment) using *W-P* model, which was treated as a stock of the organic carbon with particular adjusted yield class (AYC) in woodland. Tree organic carbon stock per hectare was drawn from *W-P* carbon model for a yield class. GIS simulated model selected the sites of particular adjusted yield class and calculated the area of the sites and then multiplied tree carbon stock per hectare from *W-P* model, to get total tree organic carbon stock for the study area.

3.3.2.1.1 Adjusted yield class (theoretical framework)

The following criteria were considered to calculate the adjusted yield class:

Species

The species selected for the study was Sitka spruce (*Picea sitchensis)*.

Soil

Yield classes were chosen with respect to soil class. The method of selecting yield class of Pyatt (1977) was followed. Moreover, local expert advice (Stevens, 2001) was also taken for ranking the soil types supporting vegetation. The following table illustrating the selection of yield class with respect to soil class for the study area for selected species was constructed:

Table 3.3.2 Yield class selection for *P. sitchensis* with respect to soil class.

Soil Classes	Local expert rating for plant support	Yield class Pyatt (1977)	Selected yield class
Brown Earths	14	16+	20
Brown Alluvial	14		
Alluvial Gley	13	16+	18
Cambic Stagno Gley	12		
Sandy Gley	11	14+	16
Brown Podzolic	10		
Humic Brown Podzolic	9		
Earthy eutro-amorphous Peat	8	12+	14
Humic Gley	7		
Ferric Stagnopodzols	6	12	12
Ironpan Stagnopodzols	5		
Cambic Stagnohumic Gley	4	10	10
Raw Oligo-amorphous Peat	3		
Sand Parendzinas	2	8	8
Humic Rankers	1		

Altitude

Consequences of altitude (elevation) on yield of a species were estimated using the method prescribed by Busby (1973). This study considered three altitude classes:

Lower altitude = below 150 m (+) 2 m^3
Middle altitude =150 to 600 m Unchanged
Upper altitude = above 600 m (-) 2 m^3

If an area was within the limit of lower altitude then the area was awarded an addition of 2 cu m. (jumping to the next yield class) and if in the upper altitude then the site yield was reduced by 2 cu m (one step down to the next yield class). However, sites in the middle altitude yield class remain the same, as in Table 3.3.2.

Slope

Contributions of slope to yield of a species were estimated with the method prescribed by Busby (1973). Here three slope classes were considered for estimating the yield class presented in Table 3.3.2. The classes are:

Lower slope = 0^0 to 20^0 (+) 2 m^3

Middle slope = 20^0 to 45^0 Unchanged

Upper slope = above 45^0 (-) 2 m^3

The areas that are in the middle slope yield class remain the same and in the lower slope class the sites were awarded with an addition of 2 cu m (*i.e.* add another yield class because sites are sheltered). Moreover, the sites that were in upper slope, had 2 cu m. deducted from the original yield class (*i.e.* subtract one yield class).

Exposure to wind

The upland of Wales is a wind prone area. Exposure to wind is considered using DAMS score developed by the Forestry Commission.

DAMS was described in chapter two, section 2.3.3.2. Pyatt (1997) pointed out that areas over 22 DAMS score were unsuitable for *P. sitchensis* as it would be likely to blow down. Hence, the sites that were over 22 DAMS score had 2 cu m. deducted from the original yield class (*i.e.* subtract one yield class) for *P. sitchensis*. The yield class for sites below DAMS score 22.00 remain the same.

DAMS score: below 22 Unchanged

DAMS score: over 22 (-) 2 m^3

Eventually,

Adjusted Yield Class (AYC) = Selected (soil) yield class ± altitude ± slope ± exposure to wind.

Worked example:

a	b	c	d	e = a+b+c+d
Humic Ranker	Altitude(400 m)	Slope (lower)	DAMS (17)	AYC
8	0	2 cum	0	10
Brown Earth	Altitude(100)	Slope (upper)	DAMS (24)	AYC
20	2 cum	(-) 2 cum	(-) 2 cum	18

3.3.2.1.2 Estimation of tree carbon: Willis-Price (*W-P*) *carbon model*

The carbon stock of adjusted yield classes with their maximum mean annual increment was calculated with the Willis–Price (*W-P)* carbon model. The model turned the adjusted yield class into mean carbon stock in tonne per hectare. The following Figure 3.3.3 is an example of carbon stock per hectare for the study species according to yield class (the spacing of plantations are 2 metre and have line thinning) (Details are in Appendix 3.3.3).

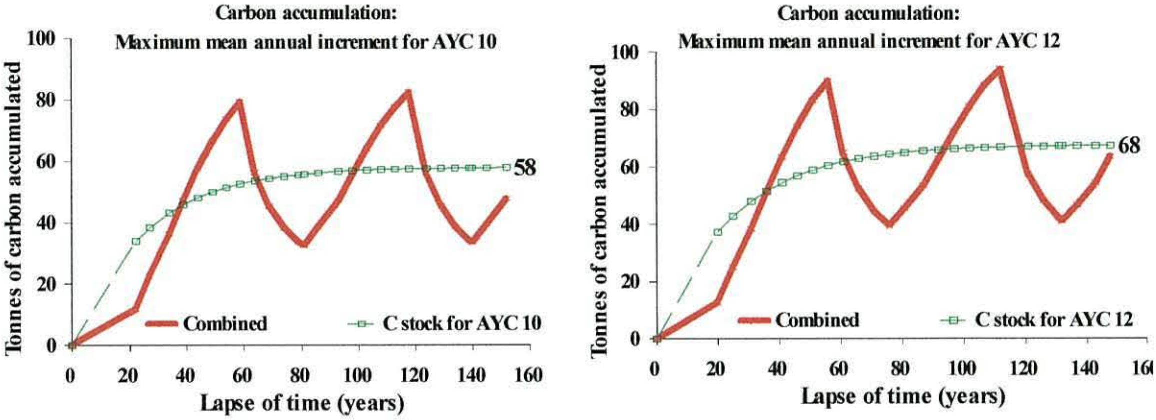


Figure 3.3.3 Carbon stock of adjusted yield class 10 and 12 of *Picea sitchensis* for maximum mean annual increment per hectare with *W-P* carbon model.

3.3.2.2 Litter carbon

Litter carbon is also a very essential part of carbon measurement for woodland. When the research was started, data for litter carbon were not available and only the layers of soils and their carbon presence per hectare were done. Later, this study considered the litter as comprising foliage, fine roots, branches and woody roots. Data regarding litter carbon were extracted from Dewar and Cannell (1992). The litter organic carbon stock is composed of total organic carbon stock of foliage, fine roots, branches and woody roots. Table 3.3.3 presents the litter organic carbon stocks with respect to yield classes for *P. sitchensis* (conifer) and *Quercus* (broadleaved) species.

Table 3.3.3 Litter organic carbon stock with respect to yield classes for *P. sitchensis* and *Quercus* species (extracted from Dewar and Cannell, 1992).

Yield Class	Litter organic carbon stock (tonnes / hectare)
P. sitchensis YC 24	29
P. sitchensis YC 22	29
P. sitchensis YC 20	26
P. sitchensis YC 18	25
P. sitchensis YC 16	23
P. sitchensis YC 14	21
P. sitchensis YC 12	19
P. sitchensis YC 10	17
P. sitchensis YC 08	14
P. sitchensis YC 06	11
Quercus spp. YC 04	20

3.3.2.3 Soil Carbon

Soil carbon was estimated with the following procedure:

A systematic approach was adopted to perceive and analyse the soil information from different sources for the study area. Soils were grouped according to Avery (1980) and the Soil Survey of England and Wales (1983) (Appendix 3.3.4). The conifer plantations within the study area have fifteen distinct soil classes. The carbon stock of the soil classes was estimated up to 1 metre depth in the various layers (horizons). The horizon names and the soil depths are presented in Table 3.3.4.

Table 3.3.4 Soil horizon depth and name with the source used.

Horizon depth (cm)	Name of horizon	Source
0 – 3	O	Avery, 1990
3 – 14	A	Avery, 1990
14 – 30	B	Avery, 1990
30 – 100	C	Avery, 1990

The organic carbon contents in percentages, their bulk density for each horizon with respective soil classes of the study area were extracted from Rudeforth *et al.* (1984), Avery (1983) and the Soil Survey of England and Wales (1983). Where no information was found local expert advice (Stevens, 2001) was taken to fulfil the study.

The calculation procedure for organic carbon for each horizon is the following:

Organic carbon presence = C1%

Depth of horizon = (Final depth – initial depth) cm = D1 cm

Bulk density = B1 gm/ cm^3

OC1 (Organic carbon gm/cm^3) = (C1 / 100) x B1

OC2 (Organic carbon gm/m^2/horizon) = OC1 x D1 x 10000

OC3 (Organic carbon tonne/ha/horizon) = (OC2 x 10000) / 1000000

Therefore, total organic carbon stock up to 1 metre depth of soil for any soil type = Addition of carbon stocks of all horizons of that soil type (Appendix 3.4.2 illustrated the soil organic carbon stock for the SNP according to soil type). An example of organising and calculating the carbon stock for the humic gley (soil type) of the study area is presented in Table 3.3.5.

Table 3.3.5 Showing how carbon stock was derived for the humic gley soil type of the study area.

Initial depth (cm)	Final depth (cm)	Org. C (%)	Org. C (gm/gm)	Bulk density (gm/cm^3)	Org. C (gm/cm^3)	Org. C (gm / m^2 /horizon)	Org. C (tonne / ha /horizon)
a	**b**	**c**	**d = c / 100**	**e**	**f = c x d**	**g = f x (b-a) x 10000**	**h = (g x 10000) / 1000000**
0	3	5.6	0.056	1.05	0.0588	1764	17.64
3	14	5.6	0.056	1.05	0.0588	6468	64.68
14	30	5.6	0.056	1.05	0.0588	9408	94.08
30	41	0.7	0.007	1.5	0.0105	1155	11.55
41	52	0.3	0.003	1.8	0.0054	594	5.94
52	100	0.2	0.002	1.45	0.0029	1392	13.92
	Total					**20781**	**207.81**

To date no research work has been published illustrating the interactions between crop productivity and soil carbon level for the Snowdonia National Park. Therefore, an experimental approach for estimating the soil organic carbon stock for the SNP is being tested here.

Assuming In equilibrium,

[carbon outflow] = [carbon input]

Again, [carbon outflow] = [carbon stock] ÷ [Residence time]

By rearrangement,

[carbon stock] = [carbon input] x [Residence time] (Price, 2001, pers. comm.)

From the above, carbon stock is proportional to carbon input for a given residence time. There is no estimate for the organic carbon input for any soil type (with specific land use such as conifer), but the input should be proportional to tree and litter carbon stock (of that landuse). Considering these views, the soil carbon stock for a given species and yield class may be estimated in the following way:

$$SO_C = SO_{CS} \times \frac{TLO_{CS}}{MOC_{TL}}$$

where, SO_C = Soil organic carbon stock per hectare, SO_{CS} = Soil type organic carbon stock per hectare, TLO_{CS} = Tree and litter carbon stock per hectare for a given species and yield class, MOC_{TL} = Mean of tree and litter organic carbon stocks per hectare which is derived from following equation:

$$MOC_{TL} = \frac{\text{Sum of tree and litter carbon stocks per hectare for all yield classes}}{\text{Total number of yield classes concerned}}$$

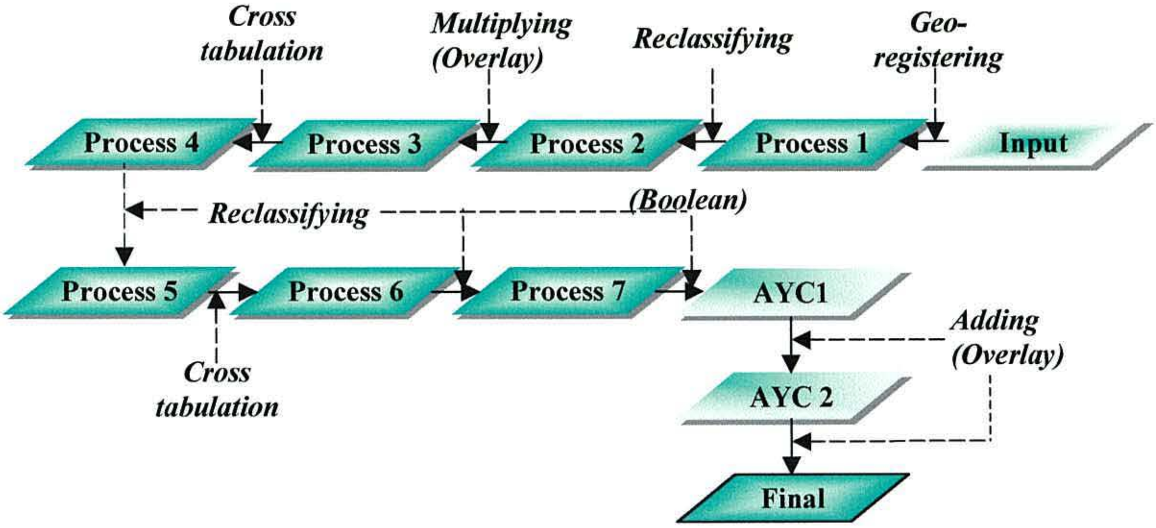
An example of organising and calculating the soil carbon stock for the humic gley (soil type) with conifer species for the study area is presented in Table 3.3.6 (Appendix 3.4.3 illustrated the soil organic carbon stock for different soil types and yield classes with conifer species of the SNP).

Table 3.3.6 Showing how organic carbon stock was derived for the humic gley soil class of the SNP considering covered with the conifer species.

Patch name	**Area (ha)**	**AYC**	**Soil type carbon stock (tonne)**	**Tree and litter carbon stock (tonne / hectare)**	**TLO_{CS} / MOC_{TL}**	**Soil organic carbon stock (tonnes)**
a	**b**	**c**	**d**	**e (TLO_{CS})**	**f = e / 91.42***	**g = b x d x f**
Humic gley						
hglelsnd	5	18	207.81	123	1.35	1398
hgmelsnd	145.75	16	207.81	111	1.21	36777
hgmemsnd	34.25	14	207.81	99	1.08	7708
Total	**185**					**45883**
***Here 91.42 is the mean of tree and litter carbon stock per hectare considering all (12) AYCs**						

3.3.2.4 GIS procedures

Geographical information system (GIS) procedure was followed to shape the theoretical frameworks into reality. Figure 3.3.4 illustrates the way spatial data were processed to locate the sites of adjusted yield classes for conifer plantations of the study area using GIS.



Legend of flow diagram:

Input = Data maps supplied from different sources.

Process 1 = Resampled maps with the same geo-register.

Process 2 = Reclassified maps with conifer species, altitude, slope, exposure to wind class and soil.

Process 3 = Multiplying (soil and conifer) boolean maps with reclassified altitude maps.

Process 4 = Process 3 maps cross tabulated with reclassified slope map.

Process 5 = Reclassified Process 4 maps to ensure only the species, soil, slope and altitude components exists in maps.

Process 6 = Process 5 maps cross tabulated with reclassified wind map.

Process 7 = Reclassified Process 6 maps to ensure only the species, soil, altitude, slope and wind components exists in maps.

AYC1 = Reclassified (Boolean) Process 7 maps to individual site to ensure only the species, altitude, slope and wind components exists in maps with respect to its soil boolean class.

AYC 2 = Same adjusted yield classes are added together to facilitate a final map indicating with sites of yield classes present in the study area.

Final = Combining all the adjusted yield classes a single map was produced .

Figure 3.3.4 Flow diagram of GIS procedure followed to locate the sites of the adjusted yield classes.

3.3.2.4.1 Description of the generic model

The following description shows how the spatial data sets are used to locate the sites of adjusted yield classes and calculate the areas of those sites, using GIS. Then these areas were used to estimate the organic carbon content of identified sites using the organic carbon model.

Input maps and Process 1

The landuse map (*mos90*) supplied by CEH was converted (*mos90co*) and resampled (*stsnp90*) to register the data from one grid system to a specified grid system covering the same area. The other input maps for soil (*snpsoilt*), elevation (*snp5con*), and slope (*snpslp*) were also geo registered to take all the maps into the same dimension. The DAMS data sets (*windsnp*) for the study area were taken from chapter 2. (Details of map analysis presented in Appendix 3.3.1, Figure 3.3.1.1 and the macro texts are in Appendix 3.3.2 of section 3.3.2.1).

Process 2

Maps produced in Process1 for species, altitude, slope, DAMS and soil were individually reclassified with the criteria mentioned in the theoretical framework. At this stage the species map (*conisnp*) indicated only the conifer plantation in the study area, the altitude map was reclassified (*alticlss*) into three classes *i.e.* from 0 to 150m, 150m to 600m and above 600m. Moreover, the slope map was reclassified (*slopclss*) into three classes and they are: below 20^0, 20^0 to 45^0 and above 45^0, and the wind map was also reclassified (*damsclss*) into two classes with DAMS score 0 to 22 and above 22. Reclassified altitude class, slope class, and wind class map was overlaid with a species map (*conisnp*) to ensure all the variables work within the area with the conifer plantation. Furthermore, the soil map of the area was reclassified (Boolean) into fifteen distinct soil classes, which were the primary criteria as stated in Table 3.3.2 (Details of map analysis presented in Appendix 3.3.1, Figure 3.3.1.1 and the macro texts are in Appendix 3.3.2 of section 3.3.2.2).

Process 3

Every soil class map was overlaid with a species map (*conisnp*). At this stage, (soil + species) map was overlaid with altitude class (*taltical*). The resultant maps showed the presence of altitude class in the conifer plantation with every soil class. (Details of map analysis presented in Appendix 3.3.1, Figure 3.3.1.2 and the macro texts are in Appendix 3.3.2.of section 3.3.2.3).

Process 4

The newly produced resultant maps in Process 3 were then cross tabulated with slope classes (*tslopecl*) to select the areas which were matched with three slope classes and with three altitude classes. (Details of map analysis presented in Appendix 3.3.1, Figure 3.3.1.2 and the macro texts are in Appendix 3.3.2 of section 3.3.2.4).

Process 5

The resultant maps in Process 4 were then sorted out considering only the area, which was combined with the specific altitude class and specific slope class. So, here the sites were selected with specific species, altitude class and slope class with respect to their soil class. (Details of map analysis presented in Appendix 3.3.1, Figure 3.3.1.2 and the macro texts are in Appendix 3.3.2 of section 3.3.2.5).

Process 6

All the maps produced in Process 5 were cross tabulated with wind class data for conifer in the study area (*tdamscl*). The resultant maps indicated the area, which were corresponded with the wind data class. (Details of map analysis presented in Appendix 3.3.1, Figure 3.3.1.2 and the macro texts are in Appendix 3.3.2 of section 3.3.2.6).

Process 7

The consequent maps from Process 6 were categorized considering only the area, combining the specific classes mentioned in Process 6 with wind classes. Therefore, the sorted sites identified with species, altitude class, slope class and wind class with respect to their soil class. (Details of map analysis presented in Appendix 3.3.1, Figure 3.3.1.2. and the macro texts are in Appendix 3.3.2 of section 3.3.2.7).

AYC 1

In Process 7 every soil class had identified sites with data of species, altitude, slope and wind classes. These sites were then isolated with the Boolean approach to notify the adjusted yield class. The sites naming was done in the following way: The first two letters indicated the soil class name, the third and fourth letters told about the altitude class, the fifth and sixth letters pointed out about slope class and lastly the seventh and eighth letters designated wind class. The following abbreviations were considered for soil classes:

Soil classes	Abbreviation
Humic Rankers	**hr**
Sand Parendzinas	**sp**
Brown Earths	**be**
Brown Alluvial	**ba**
Brown Podzolic	**bp**
Humic Brown Podzolic	**hp**
Ironpan Stagnopodzols	**is**
Ferric Stagnopodzols	**fs**
Cambic Stagno Gley	**cs**
Cambic Stagnohumic Gley	**ch**
Allvial Gley	**ag**
Sandy Gley	**sg**
Humic Gley	**hg**
Raw Oligo-amorphous Peat	**rp**
Earthy eutro-amorphous Peat	**ep**

For altitude, slopes and the wind classes following abbreviations were used in naming the site:

Altitude classes	Abbreviation	Slope classes	Abbreviation	Wind classes	Abbreviation
Lower	**le**	Lower	**ls**	Under	**nd**
Middle	**me**	Middle	**ms**	Over	**yd**
Upper	**ue**	Upper	**us**		

These abbreviations facilitated the calculation of the sites of adjusted yield classes while also used in the naming of the site. (Details of map analysis presented in Appendix 3.3.1, Figure 3.3.1.3. and the macro texts are in Appendix 3.3.2 of section 3.3.2.8).

AYC 2

Sites were selected and combined with their respective adjusted yield class. (Details of map analysis presented in Appendix 3.3.1, Figure 3.3.1.4 and the macro texts are in Appendix 3.3.2 of section 3.3.2.9).

Final

All the sites with the adjusted yield classes (AYC) were combined together to lead to a single map. Using GIS function AREA, total area with respect to every AYC was calculated to estimate the carbon accumulation (Details of map analysis presented in Appendix 3.3.1, Figure 3.3.1.5 and the macro texts are in Appendix 3.3.2 of section 3.3.2.10).

This study used GIS procedures for selecting the appropriate sites, calculated the area of the sites and then used a spreadsheet to estimate the organic carbon content of the trees and surface soils (to 1 metre depth) using organic carbon model.

3.3.2.5 Validation procedure for adjusted yield class

The GIS simulated adjusted yield classes were validated with the yield classes found in the recent survey (in 2000) conducted by the Forestry Commission for the Gwydyr Forest in the Snowdonia National Park. The hard copy of the survey was found and it only mentioned the compartment grid position (42 compartments data sets: compartment nos.1229, 1231-50, 1252-63, and 1265-72) of the yield classes. No map was available to indicate the yield class and area demarcation. Therefore, a windowed map was created to accommodate the maximum and minimum grid range. The compartments were assumed to be square in size. Samples were drawn following Mason *et al.* (1991) from the grid reference of yield classes of conifer species.

Calculation of four corner positions using x and y coordinates of compartments

The compartment grid references were found from the document with the area it occupied in hectares. To make the area into a square shape the total area was converted into square metres:

Area in hectare A1= A1 x 10000 sq. m

Then the length of an arm of the square, L1 = √ (A1 x 10000) m

The locations of the four points constructing the square around the main grid reference are: (x + L1/2, y + L1/2), (x + L1/2, y - L1/2), (x - L1/2, y + L1/2), (x - L1/2, y - L1/2)

Vector files

Vector files were created with the stated grid references as sample YC6, sample YC10, sample YC12, sample YC14, sample YC16, sample YC18, and sample YC20.

Adjusted yield classes of carbon model for the validation

GIS simulated adjusted yield classes of organic carbon model were generated as mentioned in the theoretical framework of section 3.3.2.1.1. The sample yield classes were overlaid on the final map and the statistics for validation were calculated.

3.3.2.5.1 Statistical procedures followed in validation

The data for validation were analysed for respective reliability. To check reliability the following statistical analyses were done:

Regression analysis

Regression analysis was done to observe the relationship between the yield classes of Forestry Commission of conifer (Sitka spruce) and the adjusted yield classes of organic carbon model using GIS. Nevertheless, there is a possibility of statistical bias, so reliability test of the models with respect to the Forestry Commission data was required. Minitab 13 was used to analyse the data.

Reliability coefficient (Intra-class correlation coefficient)

Reliability was measured following Winer (1971). The following formula was used to calculate the reliability of adjusted yield classes of organic carbon model with respect to yield classes of the Forestry Commission.

Interclass correlation coefficient (reliability coefficient), $R = \sigma_s^2 / (\sigma_m^2 + \sigma_s^2 + \sigma_e^2)$

Where σ_s^2 = Variance of samples, σ_m^2 = Variance of measures,

σ_e^2 = Variance of errors.

Estimated variance component in ANOVA is following:

Sources of variations	df	MS
Measures	1	$\sigma_e^2 + 12\, \sigma_m^2$
Samples	11	$\sigma_e^2 + 2\, \sigma_s^2$
Error	11	σ_e^2
Total	23	

The data were analysed with randomised block design by Minitab 13 and mean sum of squares were calculated for measures, samples and error.

3.3.2.6 Calculation for estimation of total sequestered organic carbon

Total organic carbon (T_{OC}) in tonne estimated for the study area for conifer was calculated by:

(Tree + Litter + Soil) organic carbon stock x Area (ha).

The same procedure was followed to calculate how much organic carbon would be sequestered by the broadleaf species oak YC 02 (scrubby forest assuming half sequestration of carbon that of YC 04), YC 04 and YC 06 in the study area.

3.3.2.7 Replacing the conifers with native broadleaved woodland using three scenarios

Three scenarios were drawn for replacing the conifer plantation in the study area with broadleaf species. Scenarios are the following:

Scenario 1. *Sites which would fix as great a carbon stock as the conifer if the sites were replaced by YC 02 of broadleaf species oak (Quercus spp.).*

The total sequestered organic carbon by tree, litter and soil with Sitka spruce and oak YC 02 was calculated for all the sites of the study area with the arithmetical calculations mentioned in section- 3.3.2.6. The changes in sequestering organic carbon between broadleaf (oak) and conifer was estimated and the changes are expressed in percentage as follows:

$$\textbf{Change}\uparrow\downarrow\ \textbf{(\%)} = \{(\textbf{Broadleaf } T_{OC} - \textbf{Conifer } T_{OC}) / (\textbf{Conifer } T_{OC})\} \times 100$$

Scenario 2. *Sites which would fix as great a carbon stock as the conifer if the sites were replaced by YC 04 of broadleaf species oak (Quercus spp.).*

Procedure followed to calculate the percentage change for sites of scenario 1 was followed to calculate the same while they were replaced by broadleaf species oak (*Quercus spp.*) with YC 4.

Scenario 3. *Sites which would fix as great a carbon stock as the conifer if the sites were replaced by YC 06 of broadleaf species oak (Quercus spp.)*

Procedure followed to calculate the percentage change for sites of scenario 1 was followed to calculate the same while they were replaced by broadleaf species oak (*Quercus spp.*) with YC 6.

3.4 Results

This part of study presents an estimate of carbon stock for conifer plantation of the study area (Snowdonia National Park) and a quantitative analysis of replacement of conifer with broadleaf species with three scenarios: sites replaced by oak (*Quercus* spp.) YC 02, YC 04, and YC 6.

3.4.1 Validation of GIS simulated adjusted yield class

Validation of GIS simulated adjusted yield classes (AYC) with the yield classes of the Forestry Commission (FC) was done by overlaying the sample yield classes (FC yield classes) on the GIS simulated map (Map 3.4.1). Following two statistical measures were performed to assess the reliability of GIS simulated adjusted yield classes.

Regression analysis

Linear regression analysis between the yield classes of the Forestry Commission (FC) survey and the GIS simulated adjusted yield class (AYC) of organic carbon model was done. The coefficient of determination (r^2) of the relationship was also calculated. Figure 3.4.1 illustrates the regression line. The regression equation is:

$$FC\ (y) = 5.0449 + 0.7528\ (AYC) \qquad r^2 = 37.64\% \qquad p = 0.034$$

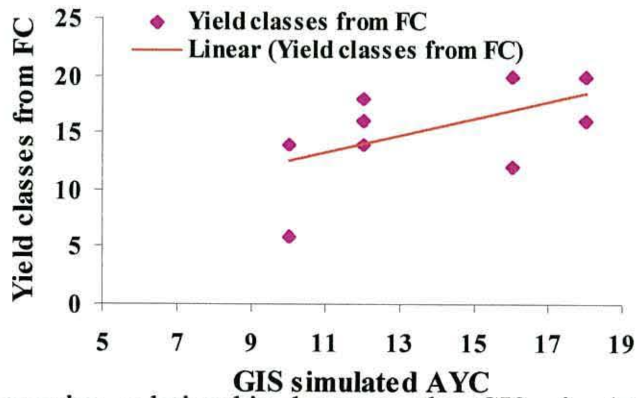


Figure 3.4.1 Regression relationship between the GIS simulated adjusted yield classes (AYC) of organic carbon model and the yield classes of the Forestry Commission (FC).

Reliability coefficient (Intra-class correlation coefficient) assessment

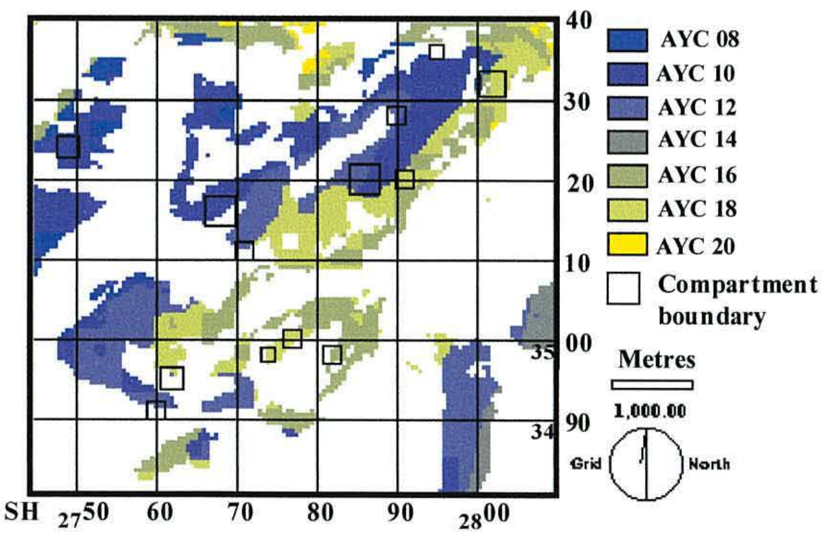
Reliability of the GIS simulated adjusted yield class with respect to the yield classes of the Forestry Commission was calculated. Table 3.4.1 illustrates the calculated reliability coefficient (R).

Table 3.4.1 Showing the calculated reliability coefficient for GIS simulated AYC.

Measure	σ^2_m	σ^2_s	σ^2_e	R
AYC with respect to YC of the Forestry Commission	0.94	8.125	5.39	**0.56**

Map for validation

Map 3.4.1 illustrates the sample data plot of sites (yield classes specified in the Forestry Commission ground survey) in Gwydyr (south) forest of the Snowdonia National Park (SNP), with the GIS simulated adjusted yield classes (AYC)



Map 3.4.1 Sample data plot of sites in Gwydyr (south) forest of SNP, with the GIS simulated adjusted yield classes (AYC).

3.4.2 Tree organic carbon

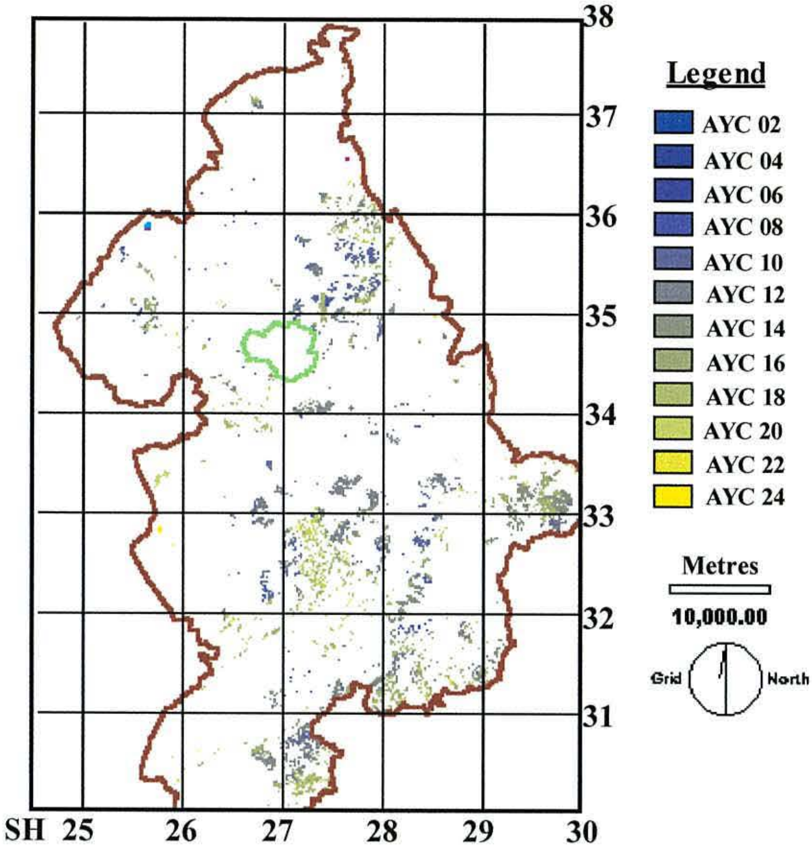
The study considered organic carbon model to calculate the carbon content for the study area (Snowdonia National Park). Map 3.4.2 shows the adjusted yield classes of conifer plantations in the study area.

Tree carbon estimation

Sites of the adjusted yield classes and their respective areas were selected and calculated using GIS. The tree carbon stock according to adjusted yield classes were calculated from the *W-P* (Willis–Price) carbon model. Then the areas were used to multiply the stocks. Carbon stock for AYC 2 and 4 were extrapolated because they were not in *W-P* model. The following Table 3.4.2 illustrates the tree carbon stock of conifer plantation with respect to adjusted yield classes.

Table 3.4.2 Estimated tree carbon stocks for conifer plantation in the study area.

Adjusted Yield Class	Total patch present	Area (hectare)	Range of patch area (hectare)	Tree carbon stock (tonnes / ha)	Total tree organic carbon stock (tonnes)
a	b	c	d	e	f = c x e
AYC 02	1	3.50	3.50	15	53
AYC 04	2	17.50	7.5-10	25	438
AYC 06	6	49.00	0.5-22.75	38	1862
AYC 08	13	411.00	0.25-350.5	49	20139
AYC 10	16	1653.75	0.25-1215.5	58	95918
AYC 12	13	3964.50	0.25-1428.5	68	269586
AYC 14	13	2785.75	0.5-270.25	78	217289
AYC 16	11	2102.50	0.75-1927.25	88	185020
AYC 18	8	2853.00	5.0-2193.25	98	279594
AYC 20	7	1125.25	1.75-541.5	108	121527
AYC 22	5	103.75	6.0-62.25	118	12243
AYC 24	2	17.75	5.75-12.0	127	2254
Total	**97**	**15087.25**			**1,205,921**



Map 3.4.2 Conifer plantations in the Snowdonia National Park (the study area) with adjusted yield classes (AYC).

3.4.3 Litter carbon

Table 3.4.3 illustrates the litter carbon stock for the conifer plantations (*Picea sitchensis)* of the study area according to the adjusted yield class. Carbon stock for AYC 2 and 4 were extrapolated because they were not in Dewar and Cannell (1992).

Table 3.4.3 Estimated litter carbon stock for conifer plantations in the study area.

Adjusted Yield Class	**02**	**04**	**06**	**08**	**10**	**12**	**14**	**16**	**18**	**20**	**22**	**24**
Litter C stock (tonnes/ha)	5	8	11	14	17	19	21	23	25	26	29	29
Total litter carbon (tonnes)	18	140	539	5754	28114	75326	58501	48358	71325	29257	3009	515

3.4.4 Soil organic carbon

Soil organic carbon stock per hectare was estimated according to the soil class with respect to the depth of horizon. Here, **O** horizon connotes 0 to 3 cm depth; **A** horizon stands for 3 to 14 cm depth; **B** horizon denotes 14 to 30 cm and **C** horizon designates 30 to 100 cm depth of soil. Figures 3.4.2 and 3.4.3 illustrate the carbon per hectare of distinct soil classes of the study area with respect to horizon.

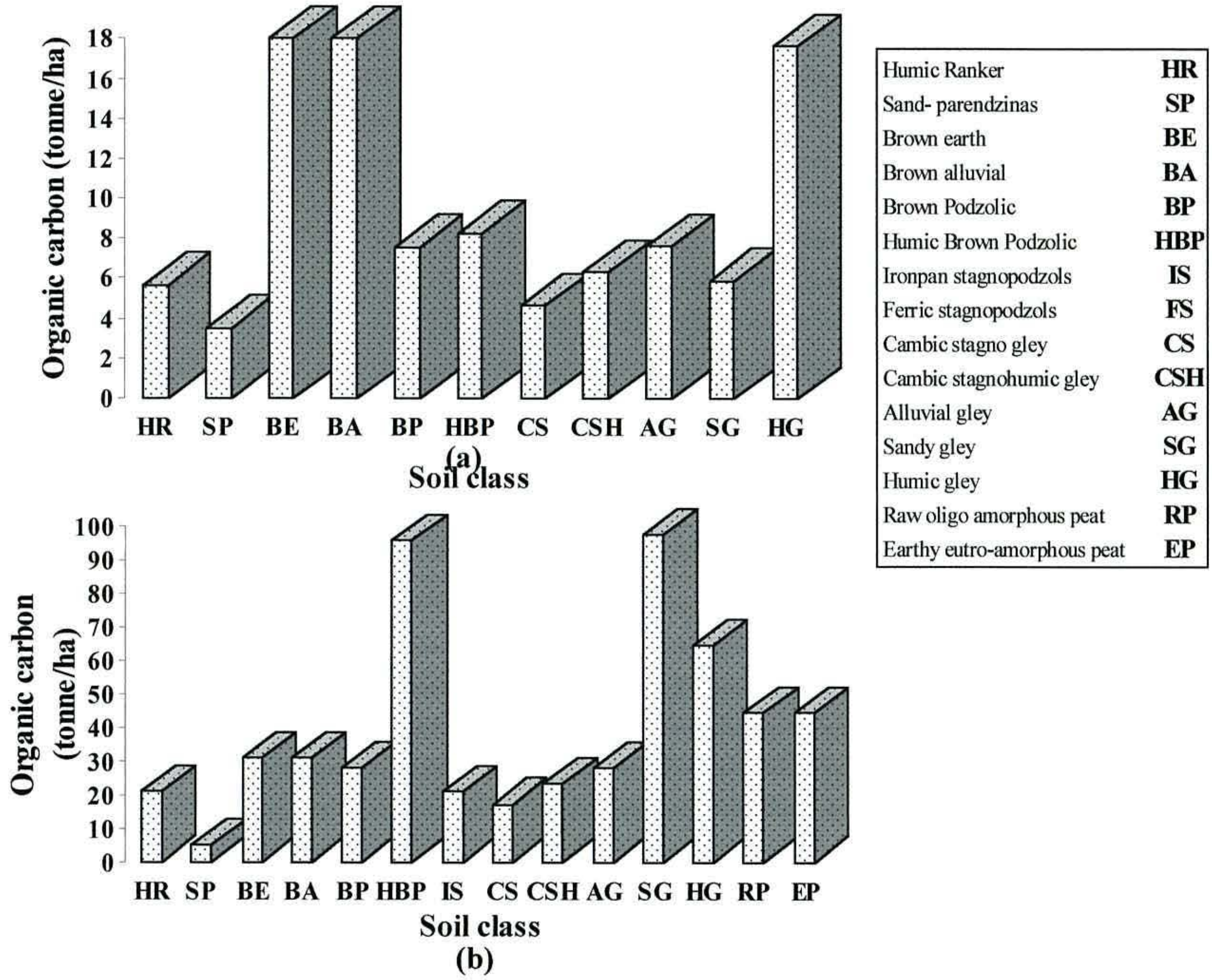
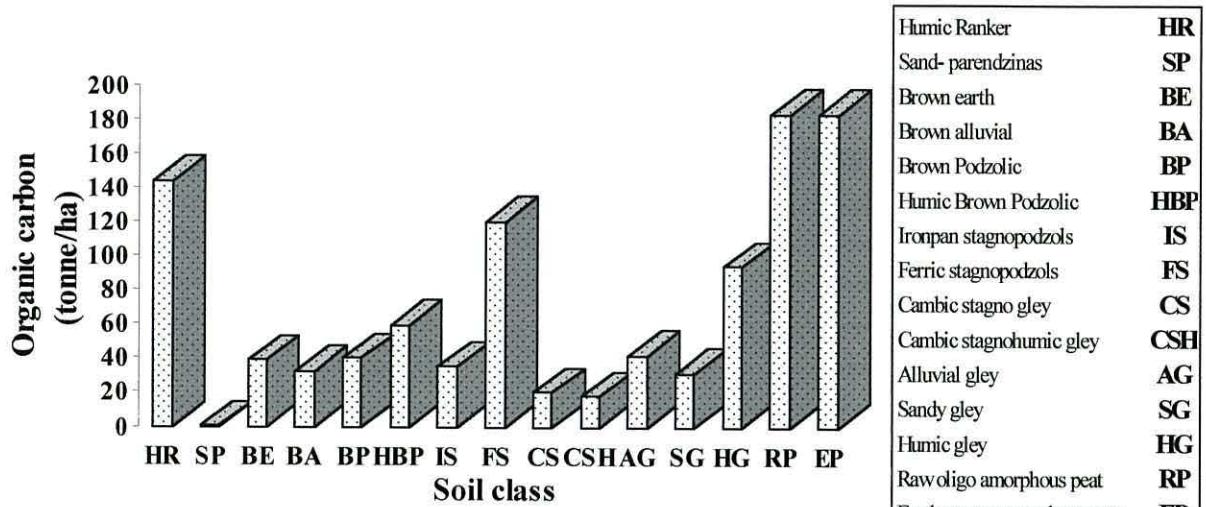
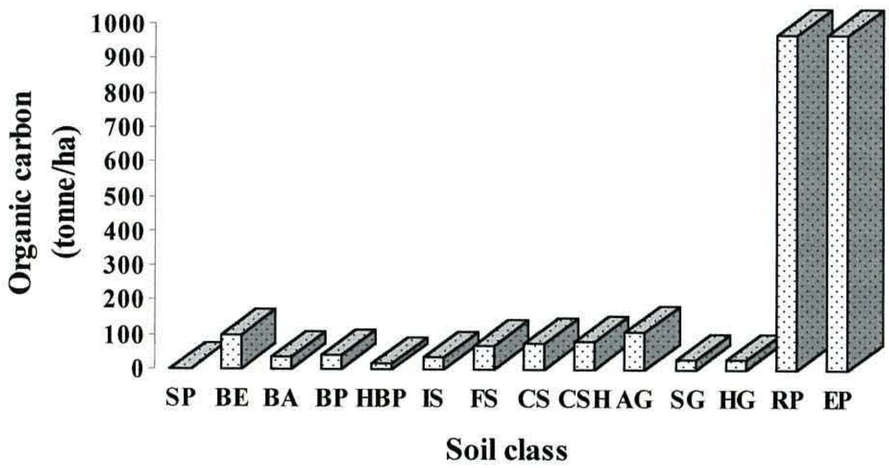


Figure 3.4.2 (a) Soil organic carbon per hectare for O horizon (0 to 3 cm) (b) Soil organic carbon per hectare for A horizon (3 to 14 cm) of soil classes in the study area. (Data in Appendix 3.4.1 Table- 1, details in Appendix 3.4.2).



(a)



(b)

Figure3.4.3 (a) Soil organic carbon stock per hectare for B horizon (14 to 30 cm) of soil classes in the study area. **(b)** Soil organic carbon stock per hectare for C horizon (30 to 100 cm) of soil classes in the study area (details in Appendix 3.4.2).

Table 3.4.4 illustrates the soil organic carbon stock to a depth of 1 metre according to soil class and adjusted yield class for the study area (details in Appendix 3.4.3).

Table 3.4.4 Soil organic carbon according to soil class and adjusted yield class of the study area (species: conifer plantations; details of soil organic carbon for each combination of soil type and adjusted yield class are in Appendix 3.4.3 and 3.4.4).

Organic carbon stock according to soil class				**Organic carbon stock according to Adjusted Yield Class (AYC)**		
Soil Class**	**Area hectare (ha)**	**Carbon stock to 1m depth (tonne/ha)**	**Total carbon stock (tonnes)**	**AYC**	**Area hectare (ha)**	**Total carbon stock (tonnes)**
a	**b**	**c**	**d**	**e**	**f**	**h**
HR	1647.25	170	218239	**AYC 02**	3.50	131
SP	5.00	11	52	**AYC 04**	17.50	1077
BE	38.75	186	11746	**AYC 06**	49.00	5305
BA	28.75	115	5283	**AYC 08**	411.00	76586
BP	5225.00	118	807637	**AYC 10**	1653.75	392024
HBP	20.50	214	5238	**AYC 12**	3964.50	2011488
IS	328.50	93	32394	**AYC 14**	2785.75	548949
FS	3632.00	192	724291	**AYC 16**	2102.50	328339
CS	558.75	119	98230	**AYC 18**	2853.00	483309
CSH	1537.00	130	186681	**AYC 20**	1125.25	198195
AG	125.50	185	32353	**AYC 22**	103.75	22462
SG	64.00	89	8373	**AYC 24**	17.75	4933
HG	185.00	208	45883	**Total**	**15087.25**	**4,072,798**
RP	1669.00	1200	1861656	****The names of soil classes are given in Figure 3.4.4**		
EP	22.25	1200	34743			
Total	**15087.25**		**4,072,798**			

Tree, litter and soil organic carbon stock

Figure 3.4.4 illustrates the tree and litter organic carbon stock per hectare with adjusted yield class and Figure 3.4.5 shows the total organic carbon stock (tree, litter and soil) per hectare according to the adjusted yield class for the study area.

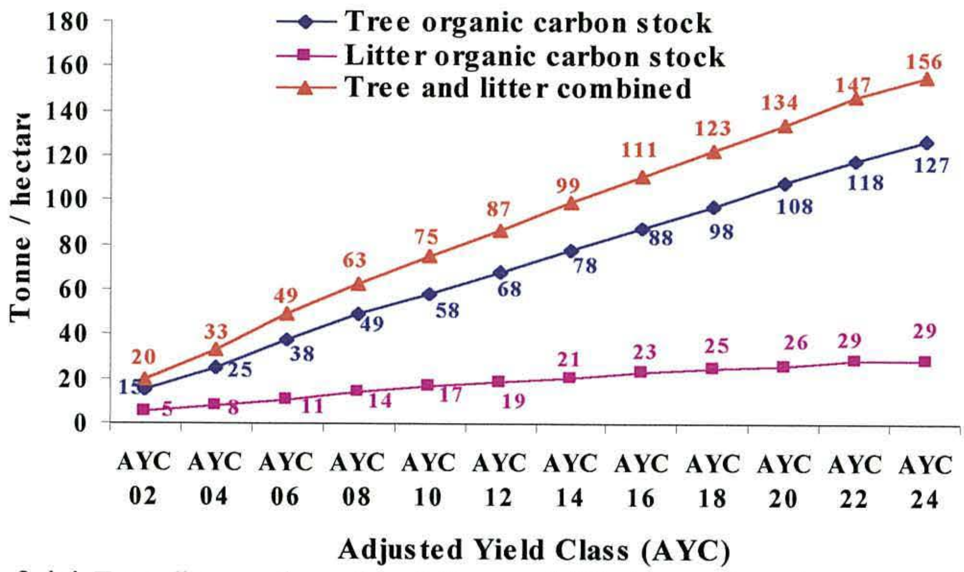


Figure 3.4.4 Tree, litter and combined (tree and litter) organic carbon accumulated per hectare with conifer species in the Snowdonia National Park (study area).

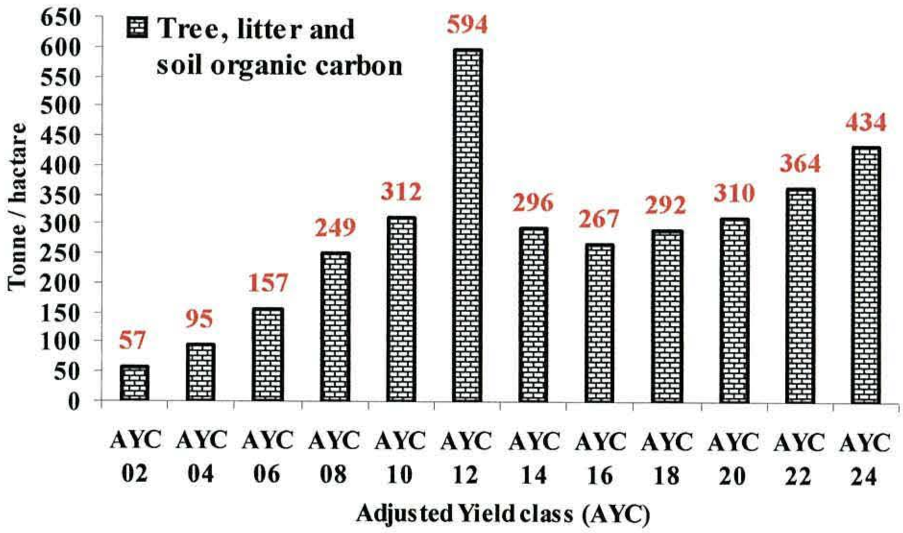


Figure 3.4.5 Total organic carbon (tree, litter and soil to a depth of 1 metre) accumulated per hectare for conifer species in the Snowdonia National Park (study area) (a greater portion of AYC 8, 10, 12 and 14 were on organic carbon rich soils; details in section 3.5.6).

3.4.4.1 Estimating total organic carbon for conifer plantations in the study area

Total organic carbon for conifer plantations in the study area was estimated by adding tree, litter and soil organic carbon stocks. Table 3.4.5 demonstrates the total organic carbon stock of the study area according to adjusted yield classes.

Table 3.4.5 Illustrates the estimation of tree, soil and litter organic carbon using adjusted yield classes for the conifer plantations in the study area (Snowdonia National Park; details estimation are in Appendix 3.4.4).

Adjusted Yield class	Area (hectares)	Tree organic carbon (tonnes)	Soil organic carbon (tonnes)	Litter organic carbon (tonnes)	Total organic carbon (tonnes)
AYC 02	3.50	53	131	18	201
AYC 04	17.50	438	1077	140	1654
AYC 06	49.00	1862	5305	539	7706
AYC 08	411.00	20139	76586	5754	102479
AYC 10	1653.75	95918	392024	28114	516055
AYC 12	3964.50	269586	2011488	75326	2356400
AYC 14	2785.75	217289	548949	58501	824739
AYC 16	2102.50	185020	328339	48358	561716
AYC 18	2853.00	279594	483309	71325	834228
AYC 20	1125.25	121527	198195	29257	348978
AYC 22	103.75	12243	22462	3009	37714
AYC 24	17.75	2254	4933	515	7702
Total	**15087.25**	**1,205,921**	**4,072,798**	**320,853**	**5,599,572**

3.4.5 Scenarios: Replacing conifer with broadleaf species

Table 3.4.6 illustrates the total organic carbon sequestered by the conifer plantations in table 3.4.5 and if these sites were replaced by oak (*Quercus* spp.) of YC 02, YC 04 and YC 06 in the study area. The table also demonstrates the changes in sequestering carbon between conifer (Sitka spruce) and broadleaf (oak) species. Three scenarios (YC 02, YC 04 and YC 06 of oak) show which would have the potential to fix as great a carbon stock as the conifer. These scenarios are also additive *i.e.* all the scenarios need to sum up (overlay) to find the total area that would store more organic carbon with oak YC 06 than conifer. Here oak YC 02 is assumed to be a scrubby forest with half the carbon stock of YC 04 for estimation of tree organic carbon stock. No data were available for litter carbon stock for YC 02 and YC 06 (oak) and hence, the estimation of total organic carbon for all yield classes of oak used the litter carbon stock of YC 04 (20 tonne/ hectare, Dewar and Cannell, 1992). Figure 3.4.6 and Figure 3.4.7 illustrate the change (%) of tree and litter, and total (tree, litter and soil) organic carbon accumulation of oak YC 02, 04 and 06 from conifer sequestration respectively.

Table 3.4.6 Demonstrates the total organic carbon stock of conifer plantations and the estimated total organic carbon for all the conifer sites being replaced by broadleaf species (*Quercus* species): YC 02 (yield class 2), YC 04 (yield class 4) and YC 6 (yield class 6) in the study area. The table also presents the percentage changes in sequestered organic carbon by broadleaved species (oak) from conifer (Sitka spruce), hence indicating three scenarios which would fix as great a carbon stock as the conifer ((a), (b) and (c) demonstrate scenarios 1, 2 and 3 respectively).

Study Area		**Total organic carbon sequestered**				**Change in carbon sequestration if conifer replaced by broadleaf**		
Adjusted Yield Class (AYC)	**Area (ha)**	**Conifer S. spruce (tonnes)**	**Br total Oak YC 02 (tonnes)**	**Br total Oak YC 04 (tonnes)**	**Br total Oak YC 06 (tonnes)**	**Oak YC 02**	**Oak YC 04**	**Oak YC 06**
AYC 02	3.50	201	564	916	1201	**(a) 181%**	357%	499%
AYC 04	17.50	1654	2818	4582	6004	**(a) 70%**	177%	263%
AYC 06	49.00	7706	8863	14413	18885	**(a) 15%**	87%	145%
AYC 08	411.00	102479	92073	149726	196193	-10%	**(b) 46%**	91%
AYC 10	1653.75	516055	389820	633913	830645	-24%	**(b) 23%**	61%
AYC 12	3964.50	2356400	1545042	2512498	3292238	-34%	**(b) 7%**	40%
AYC 14	2785.75	824739	468713	762207	998754	-43%	-8%	**(c) 21%**
AYC 16	2102.50	561716	283018	460235	603067	-50%	-18%	**(c) 7%**
AYC 18	2853.00	834228	379169	616593	807949	-55%	-26%	-3%
AYC 20	1125.25	348978	145472	236561	309977	-58%	-32%	-11%
AYC 22	103.75	37714	14360	23352	30599	-62%	-38%	-19%
AYC 24	17.75	7702	2773	4509	5908	-64%	-41%	-23%

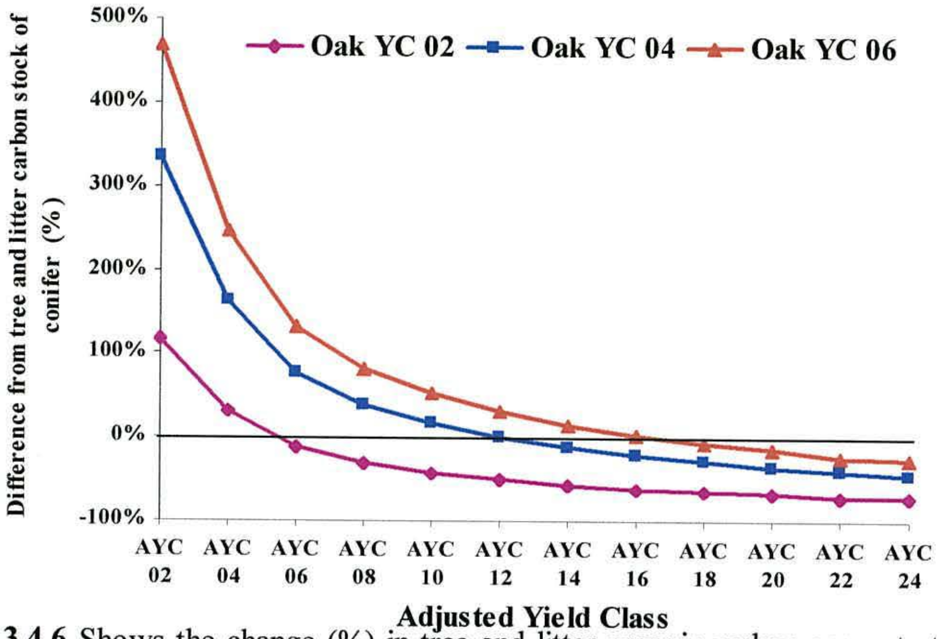


Figure 3.4.6 Shows the change (%) in tree and litter organic carbon sequestration if conifer replaced by broadleaf oak of YC 02, YC 04 and YC 06.

The graphical representation of change (%) in total organic carbon (tree, litter and soil) stock for the study area (conifer plantations of the Snowdonia National Park) is shown in the Figure 3.4.7

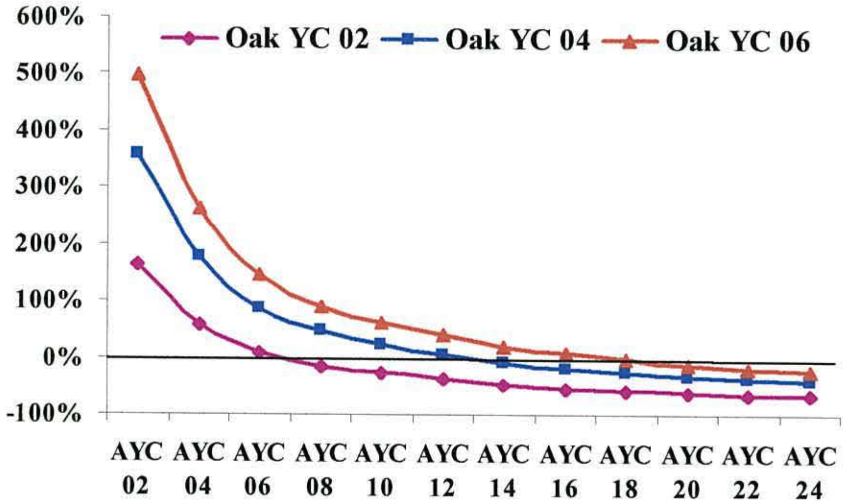


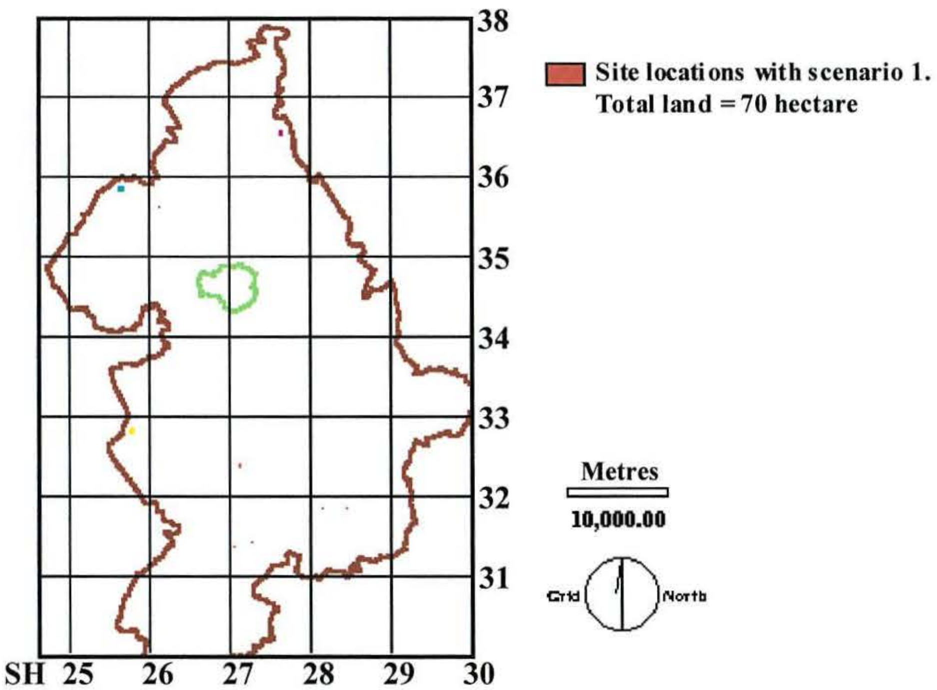
Figure 3.4.7 Shows the change (%) in total organic carbon sequestration if conifer replaced by broadleaf oak of YC 02, YC 04 and YC 06.

3.4.5.1 *Scenario 1. Sites which would fix as great a carbon stock as the conifer if the sites were replaced by YC 02 of broadleaf species oak (Quercus spp.).*

Table 3.4.7 demonstrates the sites with adjusted yield classes which are potential to fix as great a carbon stock as the conifer if the sites were replaced by the YC 02 of broadleaf species oak. Map 3.4.3 shows the area sites locations the scenario 1.

Table 3.4.7 Presents the adjusted yield classes and the area that are potential to fix as great a carbon stock as the conifer if the sites were replaced by the YC 02 of broadleaf species oak.

Adjusted Yield Class (AYC)	Area hectare	Conifer tonne	Oak YC 02 tonne	Change with Oak YC 02
AYC 02	3.5	201	564	181%
AYC 04	17.5	1,654	2,818	70%
AYC 06	49.0	7,706	8,863	15%
Total	**70.0**	**9,561**	**12,244**	**28%**



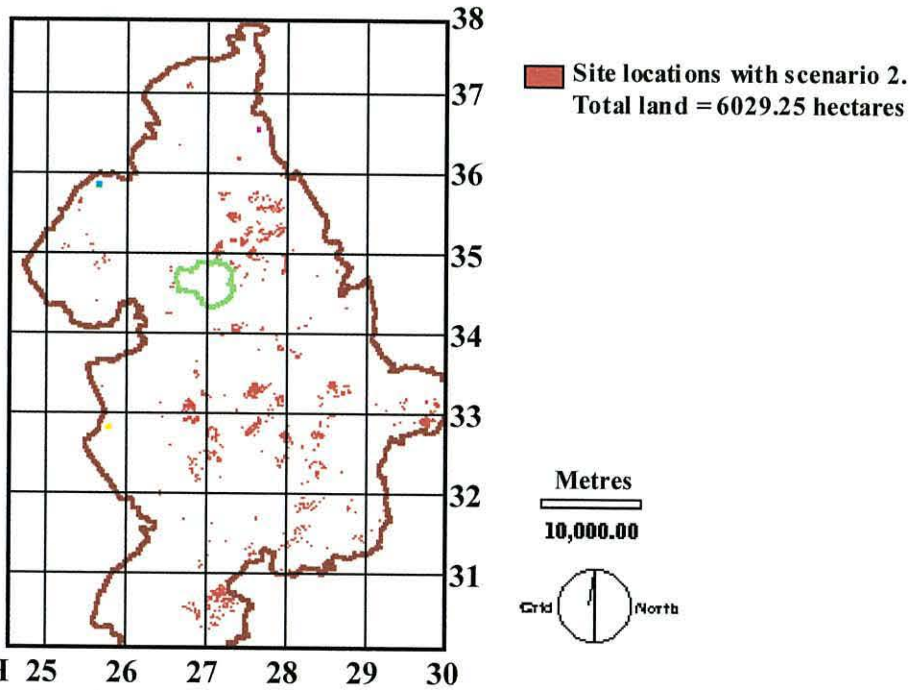
Map 3.4.3 Site locations according to the scenario 1 in the study area.

3.4.5.2 *Scenario 2. Sites which would fix as great a carbon stock as the conifer if the sites were replaced by YC 04 of broadleaf species oak (Quercus spp.).*

Table 3.4.8 demonstrates the sites with adjusted yield classes which are potential to fix as great a carbon stock as the conifer if the sites were replaced by the YC 04 of broadleaf species oak. Map 3.4.4 shows the sites locations with the scenario 2.

Table 3.4.8 Presents the adjusted yield classes and the area that are potential to fix as great a carbon stock as the conifer if the sites were replaced by the YC 04 of broadleaf species oak

Adjusted Yield Class (AYC)	Area hectare	Conifer tonne	Oak YC 04 tonne	Change with Oak YC 04
AYC 08	411	102,479	149,726	46%
AYC 10	1,653.75	516,055	633,913	23%
AYC 12	3,964.50	2,356,400	2,512,498	7%
Total	**6,029.25**	**2,974,934**	**3,296,137**	**11%**



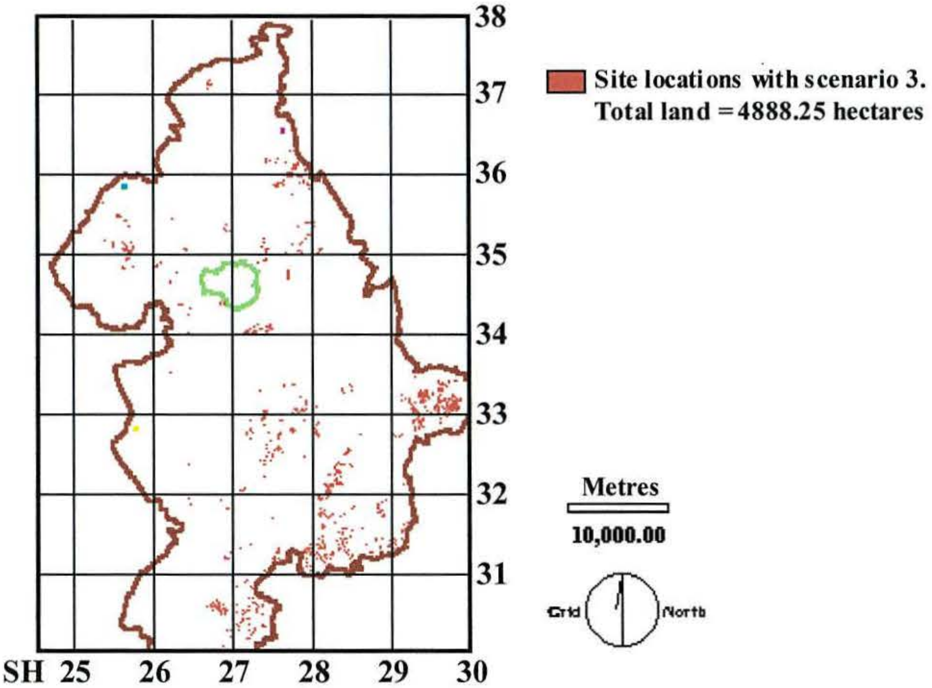
Map 3.4.4 Site locations according to the scenario 2 in the study area.

3.4.5.3 *Scenario 3. Sites which would have to fix as great a carbon stock as the conifer if the sites were replaced by YC 06 of broadleaf species oak (Quercus spp.)*

Table 3.4.9 demonstrates the sites with adjusted yield classes which are potential to fix as great a carbon stock as the conifer if the sites were replaced by the YC 06 of broadleaf species oak. Map 3.4.5 shows the sites locations with the scenario 3.

Table 3.4.9 Presents the adjusted yield classes and the area that are potential to fix as great a carbon stock as the conifer if the sites were replaced by the YC 06 of broadleaf species oak

Adjusted Yield Class (AYC)	Area hectare	Conifer tonne	Oak YC 06 tonne	Change with Oak YC 06
AYC 14	2,785.75	824,739	998,754	21%
AYC 16	2,102.50	561,716	603,067	7%
Total	**4,888.25**	**1,386,455**	**1,601,820**	**16%**



Map 3.4.5 Site locations according to the scenario 3 in the study area.

3.5 Discussion

This part considers the questions brought up in the introduction of the chapter and also interprets the results of the study.

3.5.1 Adjusted yield class prediction using GIS

A geographical information system is used to combine and analyse the spatial data concerning forest site factors. Factors like soil, elevation and exposure to wind were considered with the selected yield class of Pyatt (1977) and local expert advice. GIS simulated model was generated to predict adjusted yield classes in the study area.

3.5.1.1 Performance of adjusted yield classes

Two statistical measures were taken to assess the performance of GIS simulated adjusted yield classes with respect to the yield classes of the Forestry Commission's ground survey.

Assessing the relationship between GIS simulated model and the Forestry Commission's ground survey

The coefficient of determination of the relationship between GIS simulated adjusted yield classes and the yield classes of the Forestry Commission's ground survey was 37.64% (Section 3.4.1: Figure 3.4.1). Similar best-fit models for yield class prediction are: Bateman and Lovett (1998) (40.9%, 42.1%, 40.4% and 43%) and Tyler *et al.* (1996) (45.5% for Douglas fir, 39% for Japanese larch and 43% for Scots pine).

Reliability of GIS simulated model with respect to the Forestry Commission's ground survey

The reliability of the GIS simulated adjusted yield classes with the yield classes of the Forestry Commission ground survey were calculated through reliability coefficients (Section 3.4.1: Table 3.4.1). The reliability coefficient for adjusted yield classes of organic carbon model was 0.56. If reliability coefficient is 1, it means the adjusted yield classes are plotted as the ground survey yield classes of the Forestry Commission. Therefore, these statistical measures showed how similar the GIS simulated adjusted yield classes were to the yield classes of the Forestry Commission ground survey. However, the validation procedure had some limitations and they are:

- Only the nominal grid references of the centre of the sample compartments of the Forestry Commission's ground survey were found to validate, it might be more convincing if a map demonstrating yield classes of the ground survey was found to validate.
- The possible human error of the ground survey of the Forestry Commission was not considered.
- These types of simulation are only reliable when the data are up-to-date and maps have adequate resolution.

This simulation process has an opportunity to amend at any point with the current data, because they were written in macro language of IDRISI GIS.

3.5.1.2 Factors considered for the prediction of yield class

Species, soil, altitude, slope and exposure to wind (DAMS) are considered for yield class prediction where soil classes act as the main basis for the prediction of yield classes.

The yield classes of local expert opinion (Stevens, 2001) and the Pyatt (1977) prescription with respect to soil classes (Table 3.3.2) were restricted to a range of yield class 8 to yield class 20 (for Pyatt (1977) yield class 16). However, in practice, lower than yield class 8 and above yield class 20 were found from the FC data sets for the study area. This may suggest that Pyatt (1977) and selected yield classes with local expert opinion need adjustments with other spatial factors that contribute to estimate the yield classes for an area on the basis of soil. As soil is the main resource for the forest vegetation, local experts rated selected yield classes (Stevens, 2001; which derived from Pyatt (1977)'s prescription). These may be used as a basis for predicting the yield class with other prescriptions like Busby's guidelines that may underestimate (Macmillan, 1991) the yield class for a forest area. Models take into account the different estimated yield classes such as soil class: Pyatt (1977), altitude and slope: Busby (1974), and exposure to wind Pyatt and Suarez (1997).

Macmillan (1991) also considered similar factors but using site and soil drainage. DAMS as an exposure yardstick weighted the exposure to wind, aspect, and funnelling effects of wind. Therefore, Map 3.4.2 was used to obtain yield classes to estimate the carbon content of the conifer plantations of the study area with a minimum patch size from 0.25 hectare upwards.

3.5.2 Carbon model

The amounts of carbon stocks in trees, litter and soil were estimated. Adjusted yield classes (AYC) for the study area enabled the estimation of the total area of a patch of AYC concerned and enabled it to be a part of organic carbon estimation. The patch sizes have a potential identity chosen by the forest manager if s/he needed a specific amount of land for management. The *Willis-Price* model considered the carbon pools of trees with respect to species and yield class. Incorporating the *Willis-Price* carbon model with GIS simulated adjusted yield classes including litter and soil datasets made the conceptual model (Figure 3.3.1) into reality. Johnsen *et al.* (2001) also presented methods for quantifying carbon for component analysis that agreed with the methodology presented to estimate carbon in this study for landuse in a forest ecosystem. Figure 3.1.2 successfully followed to estimate tree and litter carbon stock using GIS for the study area.

3.5.3 Estimation of carbon storage

The conifer plantations of the Snowdonia National Park have the potential to lock up 5,599,572 tonnes where tree organic carbon contributes 1,205,921 tonnes, litter organic carbon adds 320,853 tonnes and soil organic carbon supplies 4,072,798 tonnes of organic carbon (Table 3.4.5).

The quantitative estimation procedure was followed to estimate the organic carbon contents for the study area. The tree carbon content was measured multiplying the carbon stock found in *Willis – Price* model with respect to the adjusted yield class per hectare with the land belonging to the specific adjusted yield class (Table 3.4.2). In a similar way the litter carbon was estimated according to adjusted yield class (Table 3.4.3) for the conifer plantations of the study area using the extracted data sets of Dewar and Cannell, 1992 (Table 3.3.3).

Soil organic carbon stock up to 1 metre depth was also estimated according to the soil types considering species and given yield class (soil data extracted from different published datasets; section: 3.3.2.3) for the study area (Table 3.4.4). Therefore it is possible to quantify the total organic carbon stock for the study area, where different sources of information were defined and accumulated on a single platform using GIS, with the proposed methodology. The methodology may be useful to estimate the organic carbon contents for any land use.

Adjusted yield class (AYC) 18 generated the maximum tree organic carbon stocks among other yield classes (Table 3.4.2: 279,594 tonne) but AYC 24 provided maximum carbon stock per hectare (127 tonne/ha). This was because the AYC 18 also occupied the second largest area (as AYC 10 belongs to the largest 3178 hectares) with a tree carbon stock of 98 tonne/ha, while AYC 24 only occupied 15.25 hectare. Carbon stock for AYC 02 and AYC 04 of conifer were extrapolated as no data was found to run the model to estimate the tree carbon flux for these two adjusted yield classes.

The beauty of GIS simulated model is that it can demonstrate to a user from a tiny patch (0.25 hectare) of plantation to the highest chunk of conifer (2434 hectare) with a single map for the study area (Table 3.4.2).

3.5.4 Litter carbon

Litter was composed of foliage, fine roots, branches and woody roots. The forest floor is always enriched by litter carbon, continuous litter fall and after decomposition will add a substantial amount of carbon on a regular basis. This study used the litter carbon stock from extracted data set of Cannell and Dewar

(1995) (Table 3.4.3) to estimate litter carbon content according to adjusted yield classes for the study area.

Table 3.4.3 showed the litter carbon stock for the conifer plantation of the study area. Figure 3.4.4 illustrated the pattern of tree and litter organic carbon sequestered with conifer in the study area. The estimated amount of litter organic carbon stock of conifer plantation of the study area was 320,853 tonnes.

3.5.5 Soil Carbon

There is a controversy about estimating soil (mass) organic carbon in a carbon budget. A number of researchers suggested that the soil organic carbon should be incorporated with the tree and litter organic carbon to estimate the total sequestration of organic carbon for an area with a specified landuse (Harrison *et al.* 1995; Milne and Brown, 1997; Thornley and Cannell, 2001; Tate *et al.*, 1993; Naburs and Mohren, 1993). However, Hollinger *et al.* (1993) ignored the contribution of organic carbon of soil, as they felt that it changes little, and Cannell and Dewar (1995) assumed in their carbon budget that conifer litter increased the amount of litter but did not increase the amount of organic carbon in the soil. Cannell *et al.* (1999) considered the upland organic carbon sequestration to be neutral because the ploughing of soil for afforestation lost the organic carbon sequestered by the litter of vegetation. Therefore, the buried organic carbon (soil organic carbon) was not actively accounted for in the forest carbon budget of the UK (Cannell *et al.*, 1999). However, Figure 3.5.1 showed that the high accumulation of soil organic carbon in the topsoil per hectare per centimetre (cm) depth indicates the first step of organic carbon penetration from the litter layer. Table 3.4.4 showed that in the study area a relatively small area of peat soil contained a large amount of organic carbon. Furthermore, peat soils are known as the blanket of soil organic carbon. Therefore, ignoring the soil organic carbon calculation may underestimate the total carbon estimation. Recently, Thornley and Cannell (2001) admitted the necessity of inclusion of the buried organic carbon in the carbon budget, as they found that the way the organic carbon might be lost, as assumed earlier does not happen in practice.

Soil organic carbon is also a important point for countries who are attempting to achieve the conditions agreed in the Kyoto protocol. Undisturbed long rotation forest stands provide more soil organic carbon than disturbed forests with the same species. Again, a forest with peat soil is identified as a major source or sink of organic carbon. This study suggested not doing any plantation on the peat soil since the process of plantation may disturb the soil and release huge amount of carbon to the atmosphere and act as a source of carbon. However, if the same land is allowed for natural colonisation the process of seedling establishment may be a potential sink for the future. So it is not wise to ignore the soil organic carbon from forest carbon budget, although the accumulation process of organic carbon is slow. Furthermore, the organic soil carbon account may help to find the way to the missing carbon phenomenon. Consequently, if the buried organic carbon is not considered for total carbon budget for a landuse, then it may be underestimated.

The methodology adopted to calculate the soil type organic carbon (Section 3.3.2.3) in this piece of research also agreed with Owens *et al.* (1999) and Tate *et al.* (1993). This study did not consider the annual loss or drainage of organic carbon from different soil types and environmental influences like temperature, precipitation and other climatic factors in the estimation of soil organic carbon.

The conifer plantations of the study area cover 15,087 hectares of land with fifteen distinct soil classes. The results depicted that the estimated soil organic carbon stock of the study area was about 4,072,798 tonnes up to a depth of 1 metre with organic carbon model (Table 3.4.5). The organic carbon stored in the soil is 73% of the total carbon sequestration. This estimation hypothetically considered the organic carbon content present with a specified land use (conifer plantations). So, there is no way to say that this estimation will provide the total carbon reserve in this piece of land (conifer plantations in the study area) in the soil which may be higher than the estimated carbon here. Figure 3.4.2 depicted the soil organic carbon per hectare for O and A horizon of soil classes of the study area. Brown earth, brown alluvial and humic gley soils showed the higher amount of organic carbon accumulated per hectare (Figure 3.4.2) in topsoil for conifer. The reason may be that these soil classes possessed higher adjusted yield classes of plantations (Table 3.3.3); so higher litter turnout may enrich the topsoil organic carbon. However, sand–parendzinas showed the lowest amount of organic carbon per hectare for the study area. The reasons may be two fold: the tree and litter organic carbon sequestrations with yield classes for this soil class are small and the presence of organic carbon in this soil is also low (3.9 %).

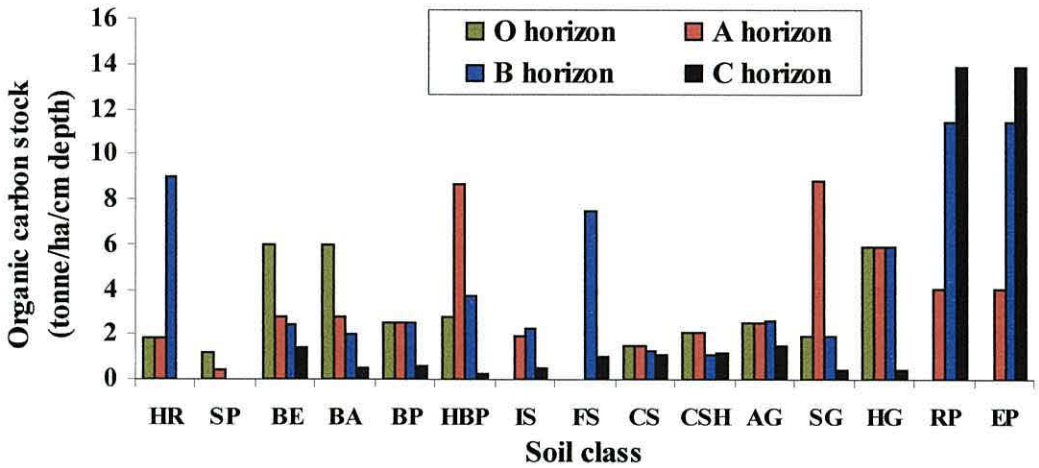


Figure 3.5.1 Soil organic carbon sequestered per hectare per centimetre depth in O, A, B and C horizon with fifteen soil classes of the study area. (Data in Appendix 3.4.1; ** Reasons for discontinuity of O and A horizon data are given below).

** Data for iron stagnopodzols, ferric stagnopodzols, raw oligo-amorphous peat and earthy eutro-amorphous peat soils of O horizon (Figure 3.4.2 and Figure 3.5.1) and ferric stagnopodzols for A horizon were not available for the study area. Rudeforth *et al.* (1984) described that these horizons are with partly decomposed litter of grasses, leaves and conifer needle; depth may be 0-15 cm for peat and stagnopodzols soils. It is assumed that they were estimated in the form of litter organic carbon.

Figure 3.4.2 and 3.4.3 illustrated the organic carbon accumulation per hectare for four layers (O, A, B, C) up to a depth of 1 metre according to soil type. Organic carbon content at these layers per centimetre depth (Figure 3.5.1) showed the topsoil of the forest contained much more organic carbon than others, which reflected the natural accumulation of organic carbon from the litter layer and the rate was subsequently lower with the depth of soil.

To estimate the soil organic carbon stocks for different land uses (conifer and broadleaf) needs a procedure to describe the interactions between organic carbon level and the contributions of land uses. The best estimate may be if any study covers the estimation of organic carbon input to the soil with respect to yield class and soil type. Unfortunately, no research has yet been published which quantifies the input of organic carbon to the soil with respect to the soil type and yield classes for the study area and an important subject for future study. Therefore, an experimental approach to estimate the soil organic carbon stock with crop productivity interactions was tested out (in section 3.3.2.3) to estimate the soil organic carbon stock for different land uses such as conifer and broadleaved woodland from the available data of the study area. This approach was used to try to estimate the organic carbon stock for broadleaf and conifer plantation using the proportionate contributions of tree and litter organic carbon stock according to the yield classes and the soil type carbon stock of the study area. It is noted that this is just one way of looking at the process of estimating the organic carbon stock of soil types for different land uses where the relevant exact information is not available.

3.5.6 Impact assessment: replacing conifer with broadleaf species

Three scenarios were presented in section 3.4.5 to show the sites for replacing conifer with broadleaf species. Table 3.5.1 presents all the scenarios with the replacement change in storing organic carbon and showing the areas with adjusted yield class (AYC) which would fix as great a carbon stock as the conifer if they were replaced by YC 02 (scenario 1), YC 04 (scenario 2), and YC 06 (scenario 3), of the broadleaf species oak. As mentioned in the section 3.4.5, these scenarios are also additive *i.e.* all the scenarios need to sum up to find the total area that would store more organic carbon with oak YC 06.

Table 3.5.1 Showing change of fixed carbon stock if the conifers were replaced by YC 02, YC 04, and YC 06 of oak ((a), (b) and (c), demonstrating scenarios 1, 2 and 3 respectively).

Study Area		**Change in carbon sequestration if conifer replaced by broadleaf**		
Adjusted Yield Class	**Area hectare**	**Oak YC 02**	**Oak YC 04**	**Oak YC 06**
AYC 02	3.50	**(a) 181%**		
AYC 04	17.50	**(a) 70%**		
AYC 06	49.00	**(a) 15%**		
AYC 08	411.00	-10%	**(b) 46%**	
AYC 10	1653.75	-24%	**(b) 23%**	
AYC 12	3964.50	-34%	**(b) 7%**	
AYC 14	2785.75	-43%	-8%	**(c) 21%**
AYC 16	2102.50	-50%	-18%	**(c) 7%**

Table 3.5.1 showed that as increase in total organic carbon (tree, litter and soil) accumulation by oak YC 02 was found when replacing up to AYC 06 of conifer (also supported in Figure 3.4.7) with scenario 1.

An increase of fixing the total organic carbon by oak YC 04 was found when replacing conifers of up to AYC 12. Scenario 2 starts from AYC 08 otherwise it may be overestimated. Table 3.4.8 showed an overall increase of 11% carbon content, which is equal to 321,203 tonnes of extra carbon fixation with YC 04 of oak than conifer (total area of scenario 2 is 6029 hectares). This increase may be due to higher tree and litter carbon stock per hectare of oak than that of conifer and a greater portion of sites under scenario 2 were on organic carbon rich soil (1666.50 hectares, 99% of the total of peat soil areas, of raw oligo-amorphous peat soil: with AYC 8: 40 ha, AYC 10: 198 ha and AYC 12: 1428.5 ha). Map 3.4.6 showed only the areas of scenario 2 in the study area.

Similarly, Table 3.5.1 showed an increase of fixing the total organic carbon by oak YC 06 when replacing up to AYC 16 conifers. Scenario 3 modelled the locked organic carbon with oak YC 06 for the areas of AYC 14 and AYC 16 conifers. Table 3.4.9 showed that the overall increase of organic carbon sequestration in scenario 3 was 16% (215,365 tonnes more organic carbon with 4888 hectares). Map 3.4.7 showed only the areas indicated in scenario 3 in the study area.

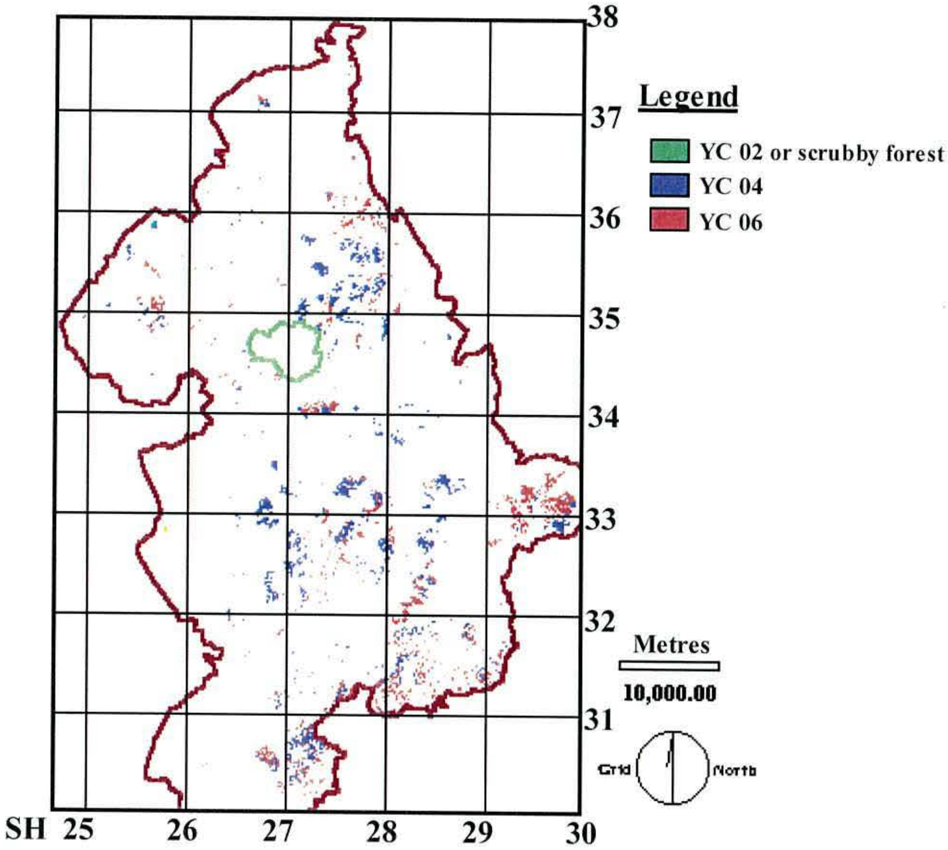
Potential areas for native broadleaved woodland

The scenarios are additive, so 10,987 hectares of land (Table 3.5.2) in three scenarios (overlaying all scenarios or reclassifying from the *dmsfinal* map, section 3.3.2.11 of Appendix 3.3.2) have the potential to fix organic carbon as great as the conifer plantations if they were replaced by oak.

Map 3.5.1 shows the potential areas in the conifer plantations of the study area which may lock as great carbon stock as the conifer if replaced by the specific yield classes of oak.

Table 3.5.2. Areas that may have potential to fix organic carbon as great as the conifer plantations of the study area if replaced with oak.

Scenarios and area		Stored organic carbon			
Scenarios	**Area hectare**	**Conifer (tonne)**	**Yield Class Oak**	**Broadleaf (tonne)**	**Overall increase over conifer**
Scenario 1	70	9,561	2	12,244	28%
Scenario 2	6,029	2,974,934	4	3,296,137	11%
Scenario 3	4,888	1,386,455	6	1,601,820	16%
Total	**10,987**	**4,370,950**		**4,910,201**	**12%**



Map 3.5.1 Site locations of the YC 02, 04 and 06 of oak which may fix organic carbon as great as the conifer plantations in the study area (existing conifer plantations of the Snowdonia National Park).

3.5.7 GIS application in organic carbon estimation and scenario determination

GIS was applied to combine data sets in the prediction of adjusted yield classes and to enable an estimate of the organic carbon of conifer plantations in the study area. GIS was used to isolate conifer plantation areas and their soil classes from the landuse and soil maps. The altitude and slope maps of the study area were combined with the soil-conifer map using simple arithmetic operations (add and multiply). GIS operations (such as reclassifying, cross tabulating and overlaying of different data sets) were used to calculate adjusted yield class (Appendices 3.3.1 and 3.3.2). Three maps were produced to show the site locations of three scenarios of the organic carbon models, these were: scenario 1: Map 3.4.5;

scenario 2: Map 3.4.6; scenario 3: Map 3.4.7. All scenarios are added together and presented in Map 3.5.1.

Macro language

Macro language of GIS is an extremely useful operation which enables total modelling in a simple form. It can explain and provide the opportunity to adopt any change in any section of the operation. It enables a forest manager to examine new policy decisions about the forest that s/he manages. Therefore, if better estimations or better data sets become available then it is easy to accommodate them with some simple changes in macro language. Otherwise it is a rather difficult and time-consuming job to do.

3.6 Summary of the chapter

A geographical information system was used to combine and analyse the spatial data for forest site factors: soil, elevation, and exposure to wind (DAMS) to predict adjusted yield class for the study area. The **a**djusted **y**ield **c**lasses (AYC) were then validated with the yield classes of the Forestry Commission ground survey. The reliability coefficient of GIS estimated adjusted yield classes was 0.56.

The *Willis-Price* tree carbon model (Price, 2001, pers. comm.) was used to estimate the carbon stock of woodland. Published data were used to estimate the litter organic carbon and local expert advice and published data were used for the soil organic carbon to a depth of one metre.

The results revealed that the conifer plantations of the Snowdonia National Park have the potential to lock up about 0.057 gigatonne where tree organic carbon contributes 0.012 gigatonne, litter organic carbon adds 0.003 gigatonne and soil organic carbon provides the main store with 0.041 gigatonne of organic carbon.

The study used three scenarios on how high the yield of oak would have to be in order to fix as great a carbon stock as the present conifer crop. The results of the study revealed that yield class 02, 04 and 06 of oak enabled the fixing of as much organic carbon as conifers of AYC up to 06, 12, and 16 respectively in the study area. The results indicated that 70 hectares of land in scenario 1 (up to AYC 06 of conifer) may lock more organic carbon if they were replaced by oak with YC 02. Similarly, 6029 hectares of land in scenario 2 (with AYC 08, AYC 10 and AYC 12 of conifer) and 4888 hectares of land in scenario 3 (with AYC 14 and AYC 16 of conifer) may lock as great a quantity of carbon if they were replaced by YC 04 and 06 of oak respectively. The scenarios are additive in showing the areas which may fix more organic carbon under oak than under conifer. Organic carbon stocks may be increased (539,251 tonnes, 12% increase) if all the areas up to AYC 16 conifer in the study area were replaced by oak. The study also considers that following natural colonisation processes, rather than using plantations, on these organic carbon rich soils such as peat, may help in the conservation of soil organic carbon.

All the scenarios have been visualised with the GIS maps. The model was written with the macro language of the IDRISI GIS to provide scope for integrating future information.

CHAPTER FOUR
CLIMATE CHANGE

4.1 Introduction

4.1.1 Climate change a decisive issue for forest management

The objective of this chapter was to develop a methodology to examine the role of spatial data and GIS in analysing the effects of climate change scenarios on a regional scale. To fulfil the main objective, the following specific objectives were set:

- to identify the sites of potential native broadleaved woodland using the potential natural vegetation site model of Mulligan (1999) for the study area;
- to examine the effects of high and low climate change scenarios (UKCIP, 1998) using the potential natural vegetation site model for 2080 (high and low) of Mulligan (1999) on the selected sites;
- to generate a macro-language based GIS model showing how spatial data sets can be used to model the climate change scenarios of Mulligan (1999).

Figure 4.1.1 shows the flow of specific objectives towards main objective.

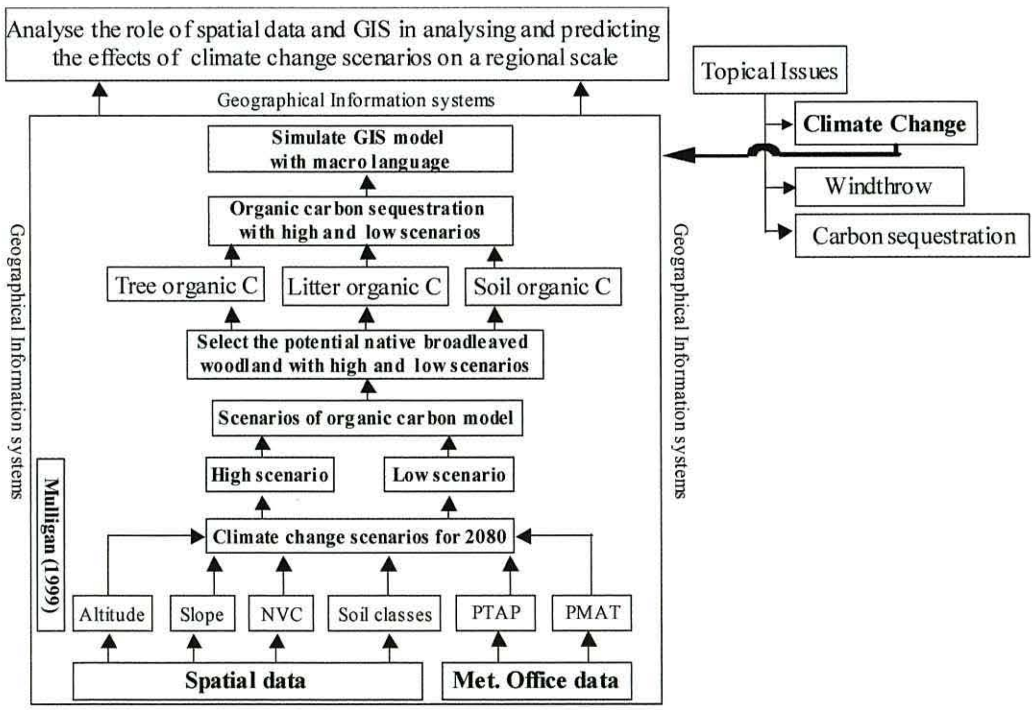


Figure 4.1.1 Illustrates the flow of specific objectives towards the main objective.

4.1.2 Background and rationale of study

4.1.2.1 Climate

Climate is a key factor which determines the distribution of plants and animals and the formation of soils through the weathering of geological materials and the decomposition or preservation of organic matter (FAO, 1995). Climate is usually defined as an average weather that measures variability over a period of time and possibly throughout a certain geographical region (IPCC, 1996). The climate in a given region involves both the average weather events and the typical extent to which conditions fluctuate from the average. On the other hand, 'weather' refers to the '*day to day changes in the state of the atmosphere at a specific location which includes temperature, humidity, windiness, cloudiness and precipitation*' (Harvey, 1999). The World Meteorological Organisation (WMO) defined 'climate' as the '*synthesis of weather conditions in a given area as defined by long term statistics of the variables of the state of the atmosphere*' (FAO, 1995). Temperature, precipitation, windiness, solar radiation, air humidity, and atmospheric CO_2 concentration are the main external climate components that drive the ecosystem (IPCC, 1996).

4.1.2.2 Kyoto Protocol

The Earth Summit 1992 - United Nations Conference on Environment and Development (UNCED) in Rio de Janeiro, brought together 178 governments to address the environment and development in a common agenda and succeeded in forming the United Nations Framework Convention on Climate Change (UNFCCC). Kyoto protocol article 2 stated that "*stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.*" UNFCCC organised the third conference of the party (COP-3) meeting, held on December 1 – 11, 1997 in Kyoto, Japan. The Parties to the UN Framework Convention on Climate Change agreed to a historic Protocol to reduce greenhouse gas emissions by harnessing the forces of the global marketplace to protect the environment (USD, 1998). This was drafted in December 1997 to provide binding, quantitative commitments for reducing national emissions of greenhouse gases to the atmosphere (Schlamadinger and Marland, 2000). Thirty-eight countries (listed as Annex B in the Protocol) agreed to reduce annual emissions for the period 2008 to 2012 by an average 5.2% below emissions in 1990. The United States agreed to a reduction of 7% (Schlamadinger and Marland, 2000). The Kyoto Protocol contains three mechanisms that have the potential to reduce the cost of meeting the Kyoto targets. The mechanisms are "Joint Implementation (JI)", "Clean Development Mechanism (CDM)", and "International Emission Trading (IET)". JI permits countries with emissions limitation commitments to fund specific emission reduction projects in other developed countries and to 'credit' the resulting emissions reductions against their obligations. CDM permits countries with emissions obligations to fund specific emission reduction projects that contribute to sustainable development in developing countries and to 'credit' the resulting emissions reductions against their obligations. IET allows countries with emissions limitation commitments to transfer part of their allowed emissions from one country to another, keeping the total allowable emissions constant (Schlamadinger and Marland, 2000). These mechanisms were set because greenhouse gases lead to global effects, it does not matter where greenhouse gases reductions occur.

4.1.2.3 Climate Change

In 1995, the United Nations Intergovernmental Panel on Climate Change (IPCC), a group of 2000 leading scientists, concluded that 'the balance of evidence suggests there is a discernible human influence on global climate'. This influence arises principally through emissions of 'greenhouse gases', which are accumulating in the atmosphere (IPCC, 1996). The work of three research groups of scientists under the umbrella of IPCC was published as 'Climate Change 1995' in three volumes (IPCC, 1996). This work, named as second assessment report to the Intergovernmental Panel on Climate Change (IPCC), accumulated most of the related work regarding climate change in a single arena as the main basis for this study up to 1995. The review presented here attempted to gather the published works after 1996 to show an up-to-date literature.

4.1.2.4 Developing the climate change scenarios adoption (CCSA) model for woodland

The United Kingdom Climate Change Impact Programme (UKCIP) anticipated that the UK climate would be warmer by between 1^0C and 3^0C by the 2080s (Hulme and Jenkins, 1998). Climate Change Impacts Review Group (CCIRG) of the UNFCCC pointed out that a 1.5^0C mean temperature increase is equivalent to a potential northward shift of 50 to 80 km per decade or an altitude shift of 40-55m per decade (CCRIG, 1996; Mulligan, 1999).

These two statements about the effects of climate change scenarios will have enormous consequences on future forestry activities, especially conversion of plantations into semi-natural woodland. The sites which are economically and environmentally viable at the present time for future native woodland, may not be sustained for the long term in terms of its relative abundance. Therefore, questions remain:

- how the national climate change scenarios can be applied at a regional scale;
- how future climate change scenarios will be evaluated for a land use change in the forestry sector;
- how the spatial data base can be utilized for implementing regional climate change scenarios to examine land use change in the future.

These questions suggest that a need exists to develop a theoretical framework and a model which would use the available spatial data sets and GIS model for future decisions for reorganising any woodland.

This study used the potential natural vegetation site model of Mulligan (1999) and the maps of three scenarios presented in section 3.4.5, to locate the suitable sites for potential native broadleaved woodland. It also used the maps for potential native broadleaved woodland for 2080 with high and low climate change scenarios of Mulligan (1999) to examine the effects of climate change scenarios on the selected sites of the study area (three scenarios presented in section 3.4.5). The following figure shows how the spatial data and the maps of Mulligan (1999) were used to construct the climate change scenario adoption model (CCSA) for the study:

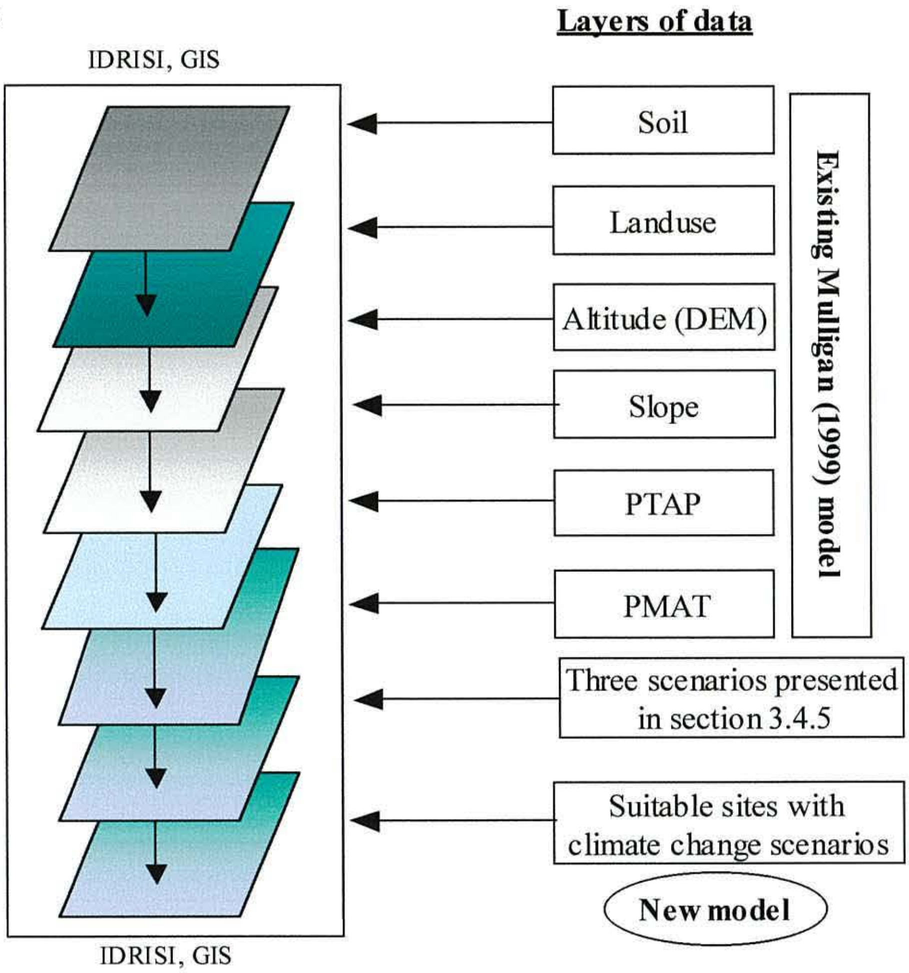


Figure 4.1.2 Exhibiting procedure to construct a climate change scenario adoption (CCSA) model using GIS.

The macro language in the IDRISI GIS was used to generate the model to provide the opportunity for the forest manager to accommodate new information, run the model and observe the effects of climate change for woodland.

4.2 Literature review

4.2.1 Climate change scenarios

According to the IPCC task group on scenarios for climate impact assessment (IPCC-TGCIA, 1999), climate scenarios are a quantitative description of the changes in climate to be expected in the future and act as the basis for assessing future impacts of climate change. These are called *scenarios* because there are no confident predictions of climate change at regional or local level such as on the scale of a farm or an individual organism. The following criteria should be met in order to choose the climate scenario to estimate the impacts of climate change (Smith and Hulme, 1998):

Criterion 1. *Consistency with global projections.* Consistent with a broad range of global warming projections based on increased concentrations of greenhouse gases;

Criterion 2. *Physical plausibility.* Physically plausible means no violation of basic laws of physics;

Criterion 3. *Applicability in impact assessments.* Illustrates the changes in spatial and temporal scales such as precipitation, solar radiation, temperature, humidity and wind speed at spatial scales ranging from global to local and temporal scales from annual to monthly values;

Criterion 4. *Representative.* They should be representative of the potential range of future regional climate change.

Historical data sets are the main footing for the climate change scenarios. Fischer *et al.* (1999) examined data for CO_2 concentration and temperature extracted from Antarctic ice cores that extended back in time through the last three glacial-interglacial transitions. To quote the authors, "*the time lag of the rise in CO_2 concentrations with respect to temperature change is in the order of 400 to 1000 years during all three glacial-interglacial transitions.*" The authors also illustrated that atmospheric CO_2 concentration exhibited no net change for approximately 15000 years, during which period air temperature dropped all the way back to values characteristics of glacial times. Hunt (1998) simulated a model illustrating substantial warming and cooling trends of global mean surface temperature with multi-decadal time scales. Hunt (1998) also suggested that much of the observed climatic variability over the past millennium may just be a reflection of natural climatic variability within the actual climate system, with occasional anomalies associated, for example, with volcanic eruptions, being superimposed on the background of natural variability. Hulme (1999) pointed out the following facts related with the scenario proposals:

- *the world has warmed by 0.4^0C to 0.8^0C since records began in 1856.*
- *over the next hundred years, the climate on Earth is likely to become warmer*
- *compared with the average for 1961-1990, global temperature increase could be between 0.6^0C and 1.4^0C by the 2020s, between 0.9^0C and 2.6^0C by the 2050s and 1.2^0C to 3.9^0C higher by the 2080s.*
- *sea level, which has risen 10-25 cm over the last century could rise two to five times faster by 2100 (a further 22-124 cm), mainly due to expansion of the world's oceans.*

Hulme *et al.* (1999) presented the record of Northern Hemisphere mean summer surface air temperature from 1000 AD to 1998 AD in the following Figure 4.2.1.

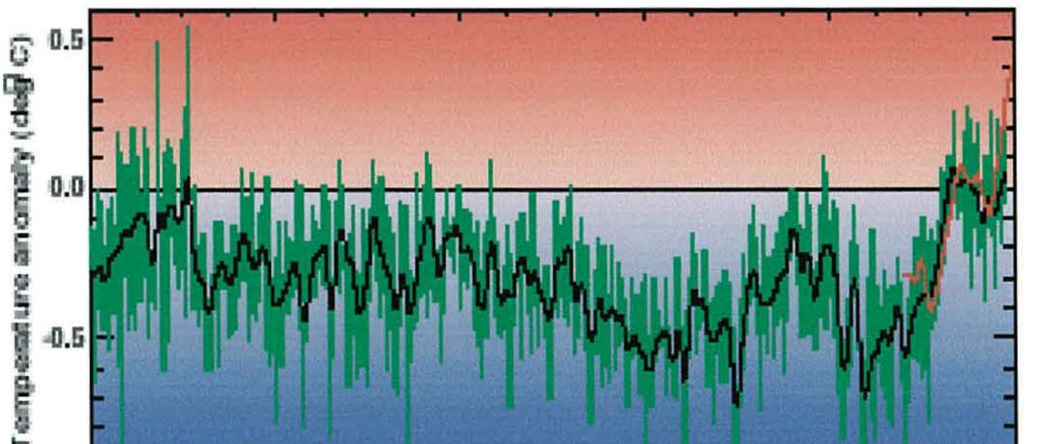


Figure 4.2.1 Northern Hemisphere mean summer surface temperature anomaly (reconstructed using palaeo-data) and expressed as deviations from the 1961-1990 average of 20.5^0C. The recent observed data are shown in red. (Adapted from Hulme *et al.*, 1999).

4.2.1.1 Basic assumptions in IPCC 1992 scenarios

The following table showing the basic assumptions taken into consideration:

Table 4.2.1 Basic assumptions made for scenarios development by IPCC (1996).

Scenarios	Population	Economic Growth	Energy Supplies
IS92 a, b	World Bank 11.3 billion by 2100	1990-2025 : 2.9% 1990-2100 : 2.3%	12000 EJ conventional oil 13000 EJ natural gas Solar costs fall to \$0.075/kwh 191 EJ of biofuels available at \$70/barrel
IS92c	UN Medium-Low case 6.4 billion by 2100	1990-2025 : 2.0% 1990-2100 : 1.2%	8000 EJ conventional oil 7300 EJ natural gas Nuclear costs declined by 0.4%
IS92d	UN Medium-Low case 6.4 billion by 2100	1990-2025 : 2.7% 1990-2100 : 2.0%	Oil and gas same as IS92c Solar costs fall to \$0.065/ kwh 272 EJ of biofuels available at \$50/barrel
IS92e	World Bank 11.3 billion by 2100	1990-2025 : 3.5% 1990-2100 : 3.0%	18400 EJ conventional oil 13000 EJ natural gas Phase out nuclear by 2075
IS92f	UN Medium-High Case 17.6 billion by 2100	1990-2025 : 2.9% 1990-2100 : 2.3%	Oil and gas same as IS92e Solar costs fall to \$0.083/ kwh Nuclear costs increased to \$0.09/k Wh

(Adapted from IPCC, 1996)

4.2.2 Global climate models

"Global climate models (GCMs) are the mathematical representations of atmosphere, ocean, ice and land surface processes on the known laws of physics describing the motion of energy and moisture" (Hulme and Carter, 1999). The

IPCC Task Group on Scenarios for Climate Impacts Assessments (TGCIA) set some criteria for the experiment on GCM and they are: An IS92a-type forcing scenario, historically-forced integrations, integrations without/with aerosol forcing and up to 2100 for greenhouse gas only, integrations with results available now and with data lodged in the public domain, and documented models (characteristics and outputs of the models are presented in Appendix 4.2.1) (IPCC-TGCIA, 1999). Considering these criteria, the following research centres of the world produced the GCMs: the UK Hadley Centre for Climate Prediction and Research (HadCM2), the German Climate Research Centre (ECHAM4), the Canadian Centre for Climate Modelling and Analysis (CGCM1), the US Geophysical Fluid Dynamics Laboratory (GFDL-R15), the Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO-Mk2), the National Centre for Atmospheric Research (NCAR-DOE), the Japanese Centre for Climate System Research (CCSR).

However, Rind (1999) described the climate model as a complex system composed of both ordered forcing and chaotic behaviour. The author concluded that future climate models would need to improve their resolution or scale because most non-linear components of the climate system operate on scales much smaller than the current GCMs. Moreover, Grassel (2000) examined the current status of the climate models especially as related to coupled general circulation models (CGCMs) and concluded that continuous evaluation and improvement of CGCMs are needed.

4.2.3 Global emission scenarios

The IPCC developed long term emission scenarios in 1990 and 1992. However, recently a set of scenarios was developed by the special report of IPCC working group III, to represent the range of driving forces and emissions in the scenario literature so as to reflect current understanding and knowledge about underlying uncertainties (IPCC, 2000).

This set of emission scenarios is known as special report emission scenarios (SRES). The 40 SRES scenarios are presented with four families (A1, A2, B1, and B2) with six scenario groups. This covers most of the range of CO_2 and other greenhouse gases (GHG). The total CO_2 emissions for the six scenario groups constitute four families. The three scenario families are A2, B1, B2 and there are three groups within the A1 family, such as A1F1 (comprising high-coal and high – oil and gas scenarios), the predominantly non-fossil fuel A1T and the balanced A1B. Figure 4.2.2 describes the four scenario families.

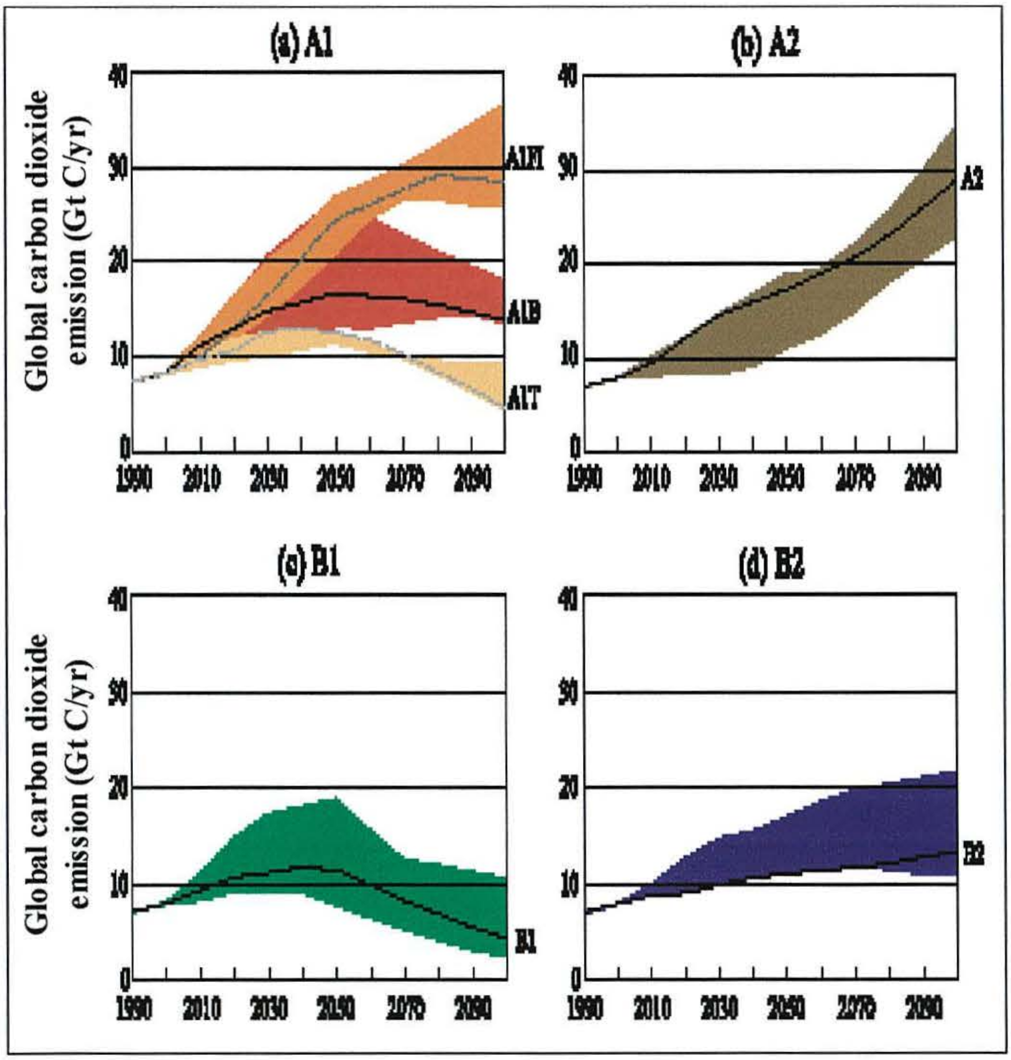


Figure 4.2.2 Total global annual CO_2 emissions from all sources from 1990 to 2100 for the families and six scenario groups. (Adapted from IPCC, 2000).

The story lines of stated emission scenarios were described in IPCC-TGCIA (1999), where it concluded as follows:

A1: A future world of very rapid economic growth, low population growth and rapid introduction of new and more efficient technologies.

A2: A differentiated world. Strengthening of regional cultural identities with an emphasis on family values and local traditions high population growth and less concern for rapid economic growth.

B1: A convergent world with rapid change of economic structures, dematerialization and introduction of clean technologies.

B2: A world in which the emphasis is on local solutions to economic, social and environmental sustainability.

SRES scenarios and their estimated environmental consequences are presented in the following table:

Table 4.2.2 SRES scenarios for 2100 by IPCC-TGCIA (1999).

Scenario estimates	1990	SRES marker scenarios for 2100			
		A1	A2	B1	B2
Population (billion)	5.252	7.1	15.1	7.2	10.4
CO_2 concentration (ppmv)*	354	680	834	547	601
Global annual mean temp change (^{0}C)**	-	2.52	3.09	2.04	2.16
Range (^{0}C)***	-	1.7-3.66	2.12-4.41	1.37-2.99	1.45-3.14
Global mean sea level rise (cm)	-	58	62	50	52
Range (cm)	-	23-101	27-107	19-90	20-93

* Best-guess assumption re. C cycle; **assuming 2.5^{0}C climate sensitivity; *** based on 1.5^{0}C and 4.5^{0}C climate sensitivity range.

4.2.4 European scenarios

The need to face the issue of climate change and reduce greenhouse gas emissions has been recognised by the European Union since the 1980s (Bortoluzzi, 2000). According to Hulme and Carter (1999) the leading features of future climate change scenarios in Europe are:

- Annual temperatures over Europe warm at a rate of between 0.1^0C/decade and 0.4^0C/decade.
- Winters currently classified as cold (occurring 1 year in 10 during 1961-1990) become much rarer by the 2020s, almost disappear entirely by the 2080s and summers (hot) become much more frequent.
- An increase in annual precipitation will occur in northern Europe, a rather smaller decrease across southern Europe and only small changes in central Europe. The base line temperature scenarios for Europe are as shown in Figure 4.2.3.

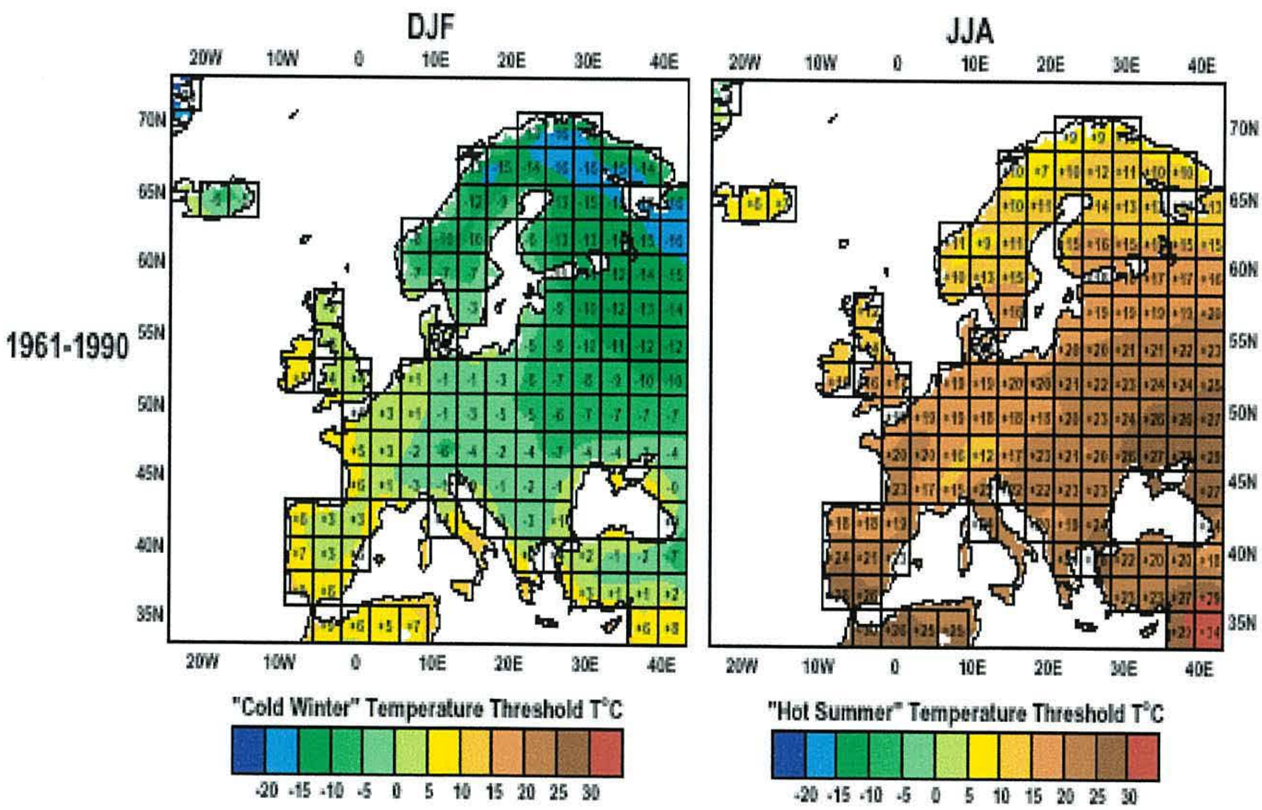
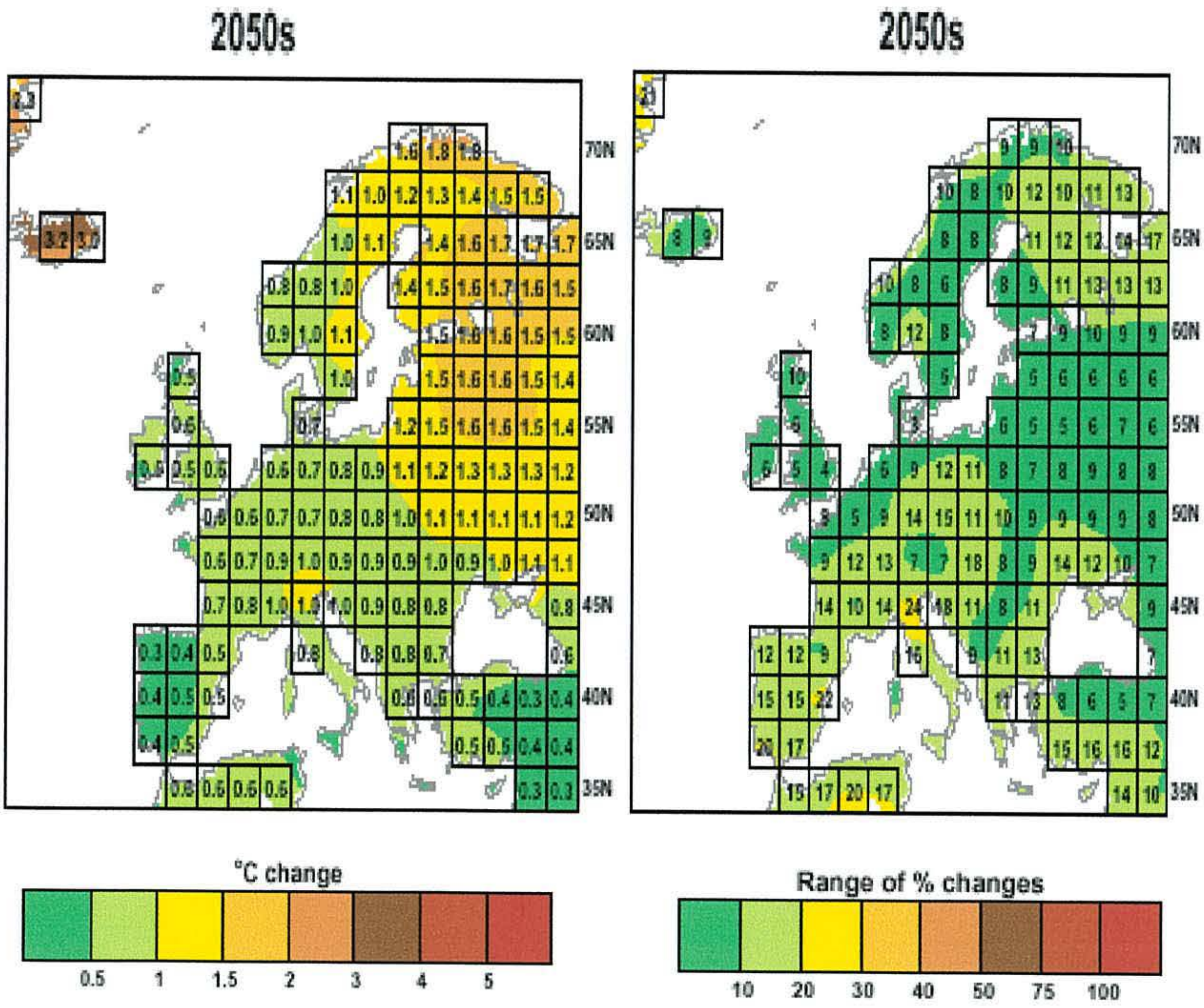


Figure 4.2.3 The average temperature threshold of 1961-1990 for winter and summer for Europe (Hulme and Carter, 1999).

Hulme and Carter (1999) also constructed climate scenarios (named ACACIA) for Europe and compared these with different scenarios which already existed. These scenarios were the product of downscaling from the global climate models (GCMs). The two examples of their predicted scenarios for winter (**D**ecember, **J**anuary and **F**ebruary) 2050s are shown in Figure 4.2.4.



(a) (b)

Figure 4.2.4 (a) Temperature change scenario for Europe for the period of 2050s: expressed with degree Celsius change and **(b)** Precipitation change scenario for Europe for the period of 2050s: expressed with range in percentage (Hulme and Carter, 1999).

4.2.5 UK scenarios

The Department of the Environment, Transport and the Regions (DETR) of the UK government established the Climate Impacts Programme for the UK (UKCIP). The most comprehensive climate scenarios for the UK have been prepared by UKCIP and the scenarios are known as UKCIP98 scenarios (spatial resolution: 250 km x 250 km). Four scenarios (Low, Medium-low, Medium-high and High) of UKCIP for considering future temperature (↑0.1^{0}C to 0.3^{0}C per decade) and precipitation change are shown in Figures 4.2.5 and 4.2.6 respectively

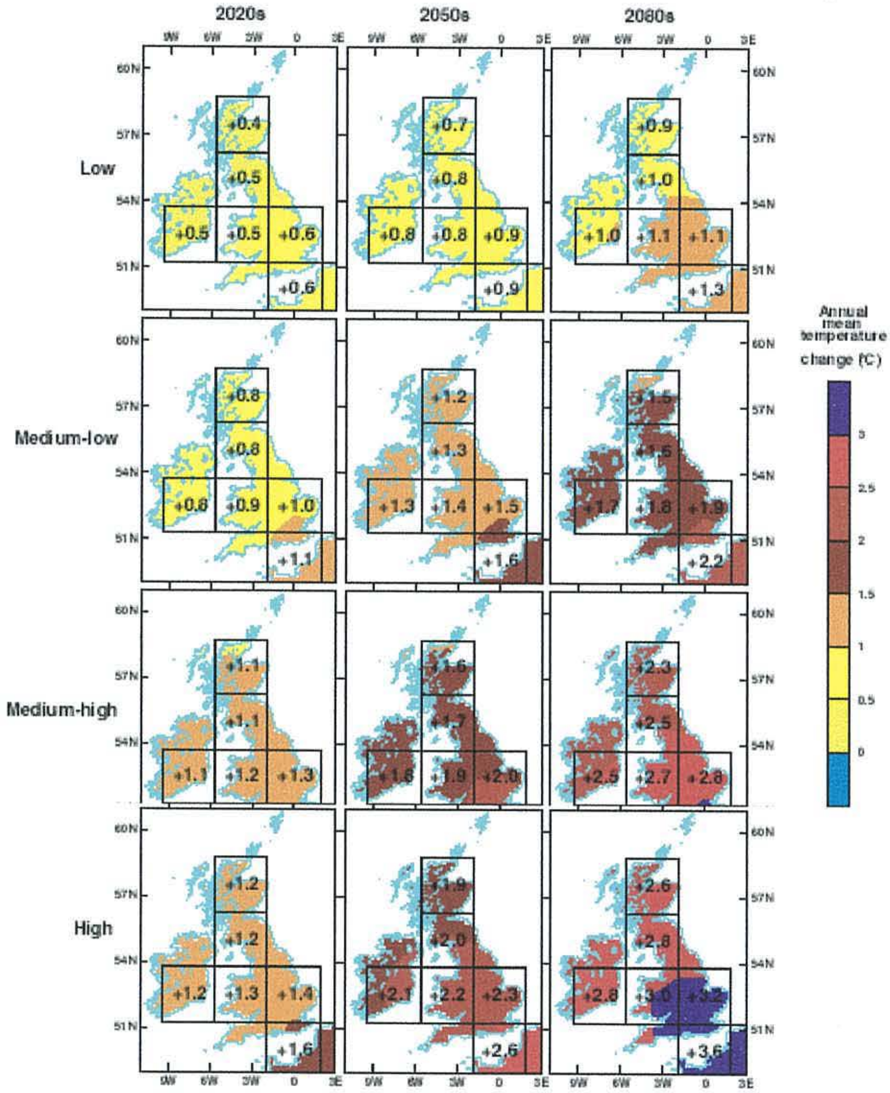


Figure 4.2.5 Changes in average annual temperature (^{0}C) with respect to 1961-1990 centred on the 2020s, 2050s and 2080s and for the four UKCIP 1998 scenarios. Highlighted numbers show the change for each model grid box over the UK (Adapted from Hulme and Jenkins, 1998)

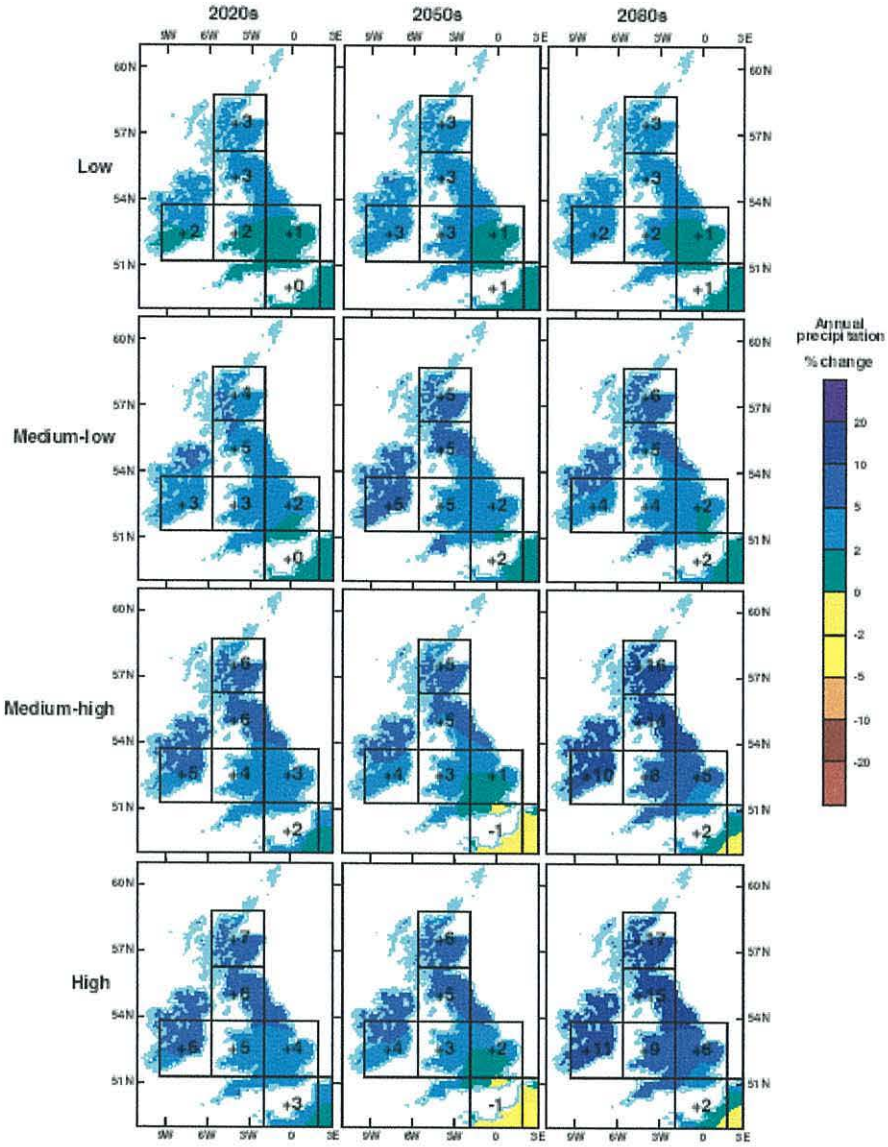


Figure 4.2.6 Changes in average annual precipitation (%) with respect to 1961-1990 centred on the 2020s, 2050s and 2080s and for the four UKCIP 1998 scenarios. Highlighted numbers show the change for each model grid box over the UK (Adapted from Hulme and Jenkins, 1998).

The temperature and precipitation scenarios also assume 0.5% per annual growth for the Low and Medium-low scenarios and 1% per annual growth for the Medium-high and High scenarios in future greenhouse gas concentration (Farrar and Vaze, 2000).

Hulme and Carter (1999) also presented the mean monthly temperatures and precipitation for 1961-1990 and five different GCMs observed over UK.

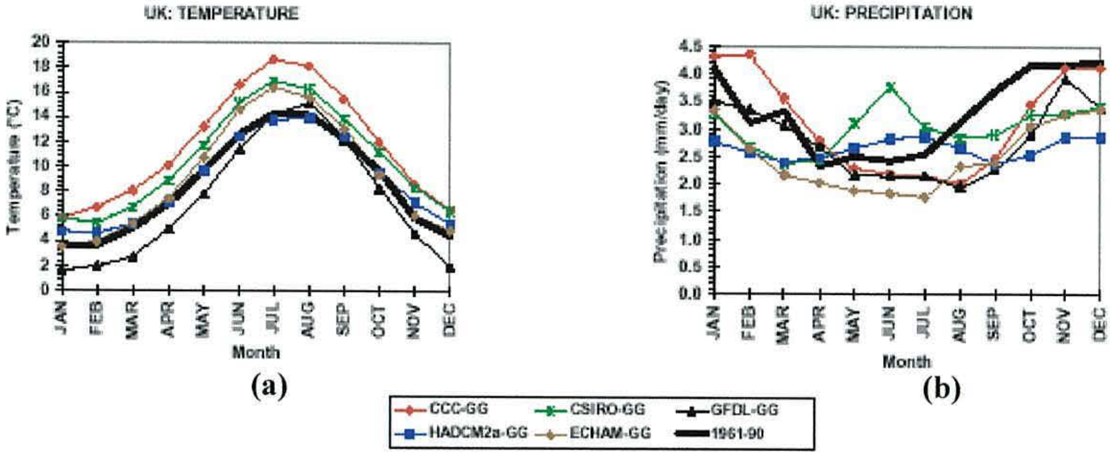


Figure 4.2.7 (a) UK temperature of 1961-1990 and five different GCMs **(b)** UK precipitation of 1961-1990 and five different GCMs (Adapted from Hulme and Carter, 1999).

The future scenarios consider CO_2 concentrations will be 515 ppmv (Low), and 637 ppmv (High) (from IPCC), 498 ppmv (Medium-Low) and 697 ppmv (Medium-high) (from HadCM2 experiments) for the period centred around the 2080s (Hulme and Jenkins, 1998). Low and high of CO_2 concentration taken from the IPCC and medium-low and medium-high were estimated from HadCM2 experiments which were not comparable with global warming rates (Hulme and Jenkins, 1998).

4.2.6 Welsh scenarios

The National Assembly for Wales (NAW) commissioned researchers with three basic questions. How will climate change affect Wales? How much do people know about climate change? And how should Wales prepare for it? Practically, these are the key questions globally. A group of researchers investigated these questions for Wales.

The researchers examined the HadCM2 model with the Medium-low scenario for the period 2080-2100 and found the following temperature and precipitation scenarios with respect to GCM (HadCM2) and regional climate model (RCM, HadCM2) scenarios for Wales.

Table 4.2.3 Mean seasonal change in temperature (^{0}C) and precipitation (%) by 2080-2100 with respect to 1961-1990 for the UKCIP98 Medium-low scenario for the 'Welsh-domain' in the GCM (HadCM2) and RCM (HadCM2). (Adapted from Hulme, 1999)

Temperature	GCM	RCM full domain	RCM land-only
Annual	2.9	2.7	2.9
Winter	3.6	3.2	3.4
Summer	2.4	2.3	2.5
Precipitation			
Annual	8.7	12.9	10.5
Winter	32.4	27.4	28.0
Summer	-24.9	-16.0	-21.4

Moreover UKCIP predicts (Farrar and Vaze, 2000) that by 2080 Wales will experience:

- greater warmth all year round — by 1.1-2.9 ^{0}c
- more precipitation in winter — by 7-24%
- less precipitation in summer — by 7-14%
- greater annual precipitation — by 2-9%
- a rise of sea level — of 18-79 cm
- a higher mean wind speed — by 1-4%
- more evapo-transpiration — by 13-27%
- more variability from year to year — no. of extreme years will increase
- rain — more frequent
- storms — violent and intense
- more drought years — by 10%
- more very severe gales — by 10%

4.2.7 Climate change scenarios for the Snowdonia National Park

Mulligan (1999) developed climate change scenarios for the Snowdonia National Park using mean annual temperature and precipitation data for North Wales (1961-1990). Combining an adiabatic lapse rate and coastal mean-annual temperature with continentality data created the present mean-annual temperature map. Mulligan (1999) considered 0.6^0C (Wheeler and Mayes, 1997) as adiabatic lapse rate per 100-metre above sea level with coastal mean annual sea level temperature of 10.3^0C. The present total annual precipitation map was also created by applying Francis' (1978) prescription; an increase of precipitation with altitude rate of 166mm per 100m and annual precipitation rate at sea level was 1025mm. The following equations were applied to create the present mean annual temperature (PMAT) map and present total annual precipitation (PTAP) map for the Snowdonia National Park (study area):

$$\mathbf{PMAT = (10.3 - 0.6H) - 0.003D} \quad \textbf{and} \quad \mathbf{PTAP = 1025 + 166H}$$

Where, 10.3 is the mean annual coastal temperature in ^{0}C, H denotes altitude in 100 m above sea level, D represents the distance per 100 m from the coast, 1025 is the sea level total annual precipitation level in mm, and 166 presents the altitudinal gain rate of precipitation in mm.

4.2.8 National Vegetation Classification (NVC)

Mulligan (1999) generated potential national vegetation classification sites after referring to the work of Armenteras (1996) and Schumacher (1997) for the Snowdonia National Park using GIS. Mulligan (1999) marked only the areas containing W4, W7, W9, W11, and W17 NVC classes (Species compositions with altitude and climate range described in Appendix 4.2.2). The main features considered for marking the NVC woodlands were:

W4 considered: soil - cambic stagno gley and sandy gley; slope - 0^0 to 10^0; altitude - 250 m to 400m. **W7** considered: soil - ferric stagnopodzols, cambic stagnohumic gley and alluvial gley; slope - 0^0 to 10^0; altitude - 250 m to 300m.

W9 considered: soil-ferric stagnopodzols; slope-0^0 to 16^0; altitude-250m to 400m.

W11 considered: soil - sand parendzinas, brown earth, brown alluvial and brown podzol; slope - 0^0 to 60^0; altitude - 250 m to 650m. **W17** considered: soil - humic ranker, brown alluvial, brown podzols, humic brown podzol and ironpan stagnopodzols; slope - 0^0 to 45^0; altitude - 250 m to 650m.

Armenteras (1996) demarcated areas with W9, W11 and W17 NVC classes of the study area. The study considered only woodlands that might develop on uplands over 250m above mean sea level. Armenteras (1996) conducted a good review about NVC for upland Welsh forest. Whitbread and Kirby (1992) also described the NVC woodland types. The following Figure 4.2.8 illustrates the flow which may be considered in the critical management decision process for the encouragement of natural regeneration of conifers (Nixon and Worrell, 1998).

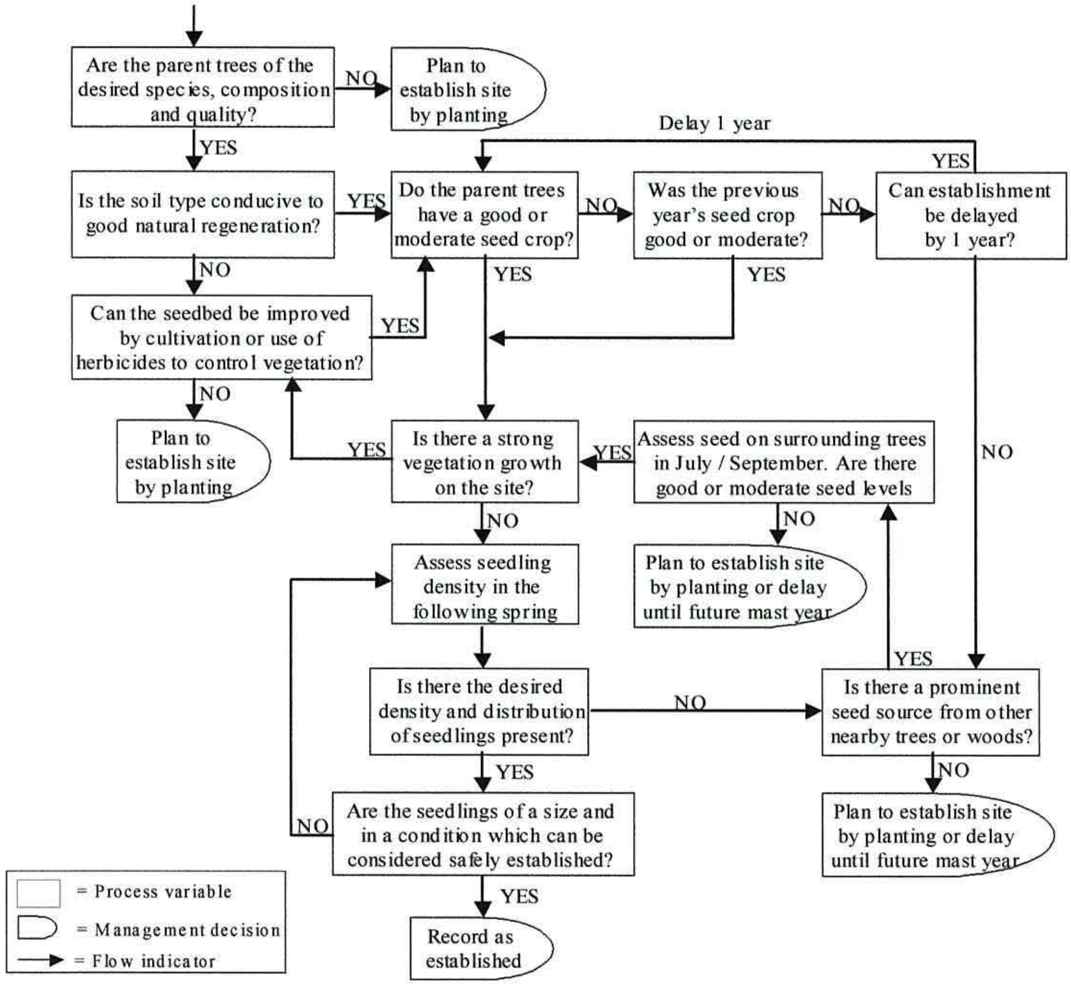


Figure 4.2.8 Major factors influencing the management decision of conifer stands to encourage natural regeneration. (Adapted from Nixon and Worrell, 1998).

4.3 Materials and methods

This part presents the model developed for the application of climate change scenarios for the study area (sites located in three scenarios of section 3.4.5), including the details of data and maps used in the model through a case study. Methodologies adopted to run the model and to demonstrate the methods using the maps of Mulligan (1999) to identify the suitable sites for future vegetation using GIS are also presented.

4.3.1 Model

This piece of research used three maps of Mulligan (1999) describing potential native broadleaved woodland for the Snowdonia National Park (SNP) (*Potwd*) and potential native broadleaved woodland with high and low climate change scenarios for 2080 (*nvc80h*, *nvc80l*) for the SNP.

Mulligan (1999) used UKCIP 1998 climate change scenarios (high and low) to generate the maps for climate change scenarios for the Snowdonia National Park. Mulligan's (1999) maps were then overlaid on the maps of the study area (sites located in three scenarios of section 3.4.5) to locate the potential native broadleaved woodland for the stated sites and also to examine the effects of climate change scenarios using GIS. Figure 4.3.1 portrays the GIS simulated climate change scenarios adoption (CCSA) model.

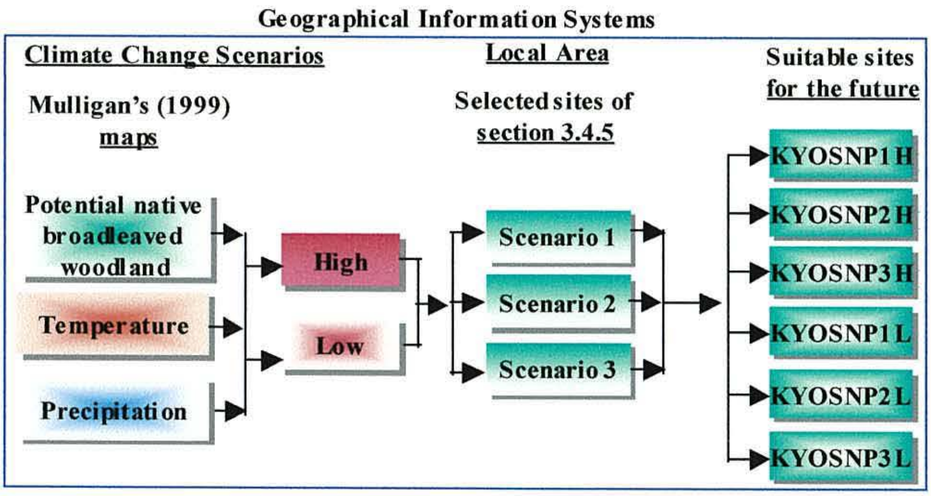


Figure 4.3.1 Flow scheme demonstrating the climate change scenarios adoption model for study species in the Snowdonia National Park (SNP).

4.3.2 A case study: Application of the model in the study area

The model was applied to develop a GIS procedure to locate suitable sites for **p**otential **n**ative **b**roadleaved **w**oodland (PNBW) for the present and future (2080) using the maps of Mulligan (1999) and the maps of three scenarios of section 3.4.5. The model also examined the effects of climate change scenarios on sites that are able to lock at least as great a carbon stock as conifer if they were replaced with the native broadleaved species oak (presented in section 3.4.5). Details of the study area (Snowdonia National Park) including its geology, soil, climate, land uses and ownership were described in section 2.3.3.1.

4.3.2.1 Data sources

Three main sources were used to collect data and they are:

Maps of Mulligan (1999)

Mulligan (1999) supplied the following maps:

1) Potential natural vegetation woodland (*potwd*) which illustrated the sites of potential native broadleaved woodland for the Snowdonia National Park for the present time;
2) Potential natural vegetation woodland for 2080 with a high climate change scenario (*nvc80h*) for the Snowdonia National Park; this map located the sites of potential native broadleaved woodland for 2080, considering the high climate change scenario (temperature 3^0C↑ and precipitation 9%↑);
3) Potential natural vegetation woodland for 2080 with a low climate change scenario (*nvc80l*) for the Snowdonia National Park; this map demonstrated the sites of potential native broadleaved woodland for 2080, considering the low climate change scenario (temperature 1.1^0C↑ and precipitation 2%↑).

Mulligan (1999) applied UKCIP 1998 climate change scenarios (Hulme and Jenkins, 1998) over the present mean annual temperature (PMAT) map and the present total annual precipitation (PTAP) map of the SNP to draw the high and low climate change scenarios for 2080.

The Centre for Ecology and Hydrology (CEH)

The Centre for Ecology and Hydrology (CEH) supplied the landuse map for the study area; details of the map were described in section 2.3.3.2.

Chapter Three (Carbon sequestration)

Section 3.4.5 of chapter three (Carbon sequestration) supplied the maps of scenarios (1-3), which locate the sites that may store organic carbon at least as great as the conifer if they were replaced with the native broadleaved species oak. The soil map of the study area was taken from chapter three. Tree, litter and soil organic carbon stocks were also taken for calculating the total organic carbon contents for the sites, which are suitable for climate change scenarios. Details of these datasets were described in sections 3.4.2 to 3.4.4.

4.3.2.2 Tools used in the study

Geographical Information System: IDRISI

The main platform for the study was the IDRISI for windows version 2.0, GIS software.

Spreadsheet packages

Excel 2000 and Quattro-Pro 8 were used to organise the data and to construct the tables.

4.3.3 Methods

Three maps supplied by Mulligan (1999) were overlaid on the maps of the study area (sites located in three scenarios of section 3.4.5) to locate the potential native broadleaved woodland (PNBW) for the present time and also for 2080 with high and low climate change scenarios. Currently, the sites identified are plantations of conifer (*Picea sitchensis*) which would be able to lock at least as much carbon as the conifers if they were replaced with oak.

4.3.3.1 Geographical information system (GIS) procedure followed to run the model

This GIS procedure (Figure 4.3.2) was followed to apply the theoretical model as shown in Figure 4.3.1. Figure 4.3.2 illustrates the way data were processed to run the model for locating the sites for potential native broadleaved woodland for the present and for 2080 with high and low climate change scenarios using GIS. (Appendix 4.3.1 illustrated the map analysis).

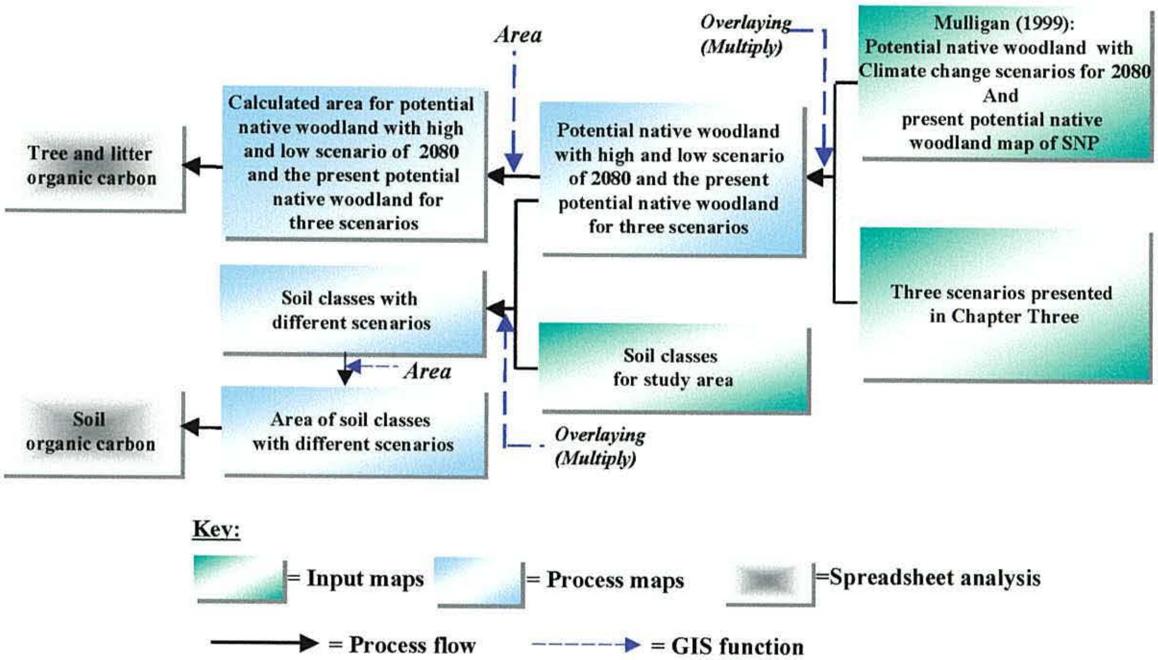


Figure 4.3.2 Flow of GIS procedure followed to locate the sites suitable for native woodland considering high and low climate change scenarios of 2080.

Five steps (Process 1 to 5) were used to generate the maps for locating the potential native broadleaved woodland for the present time and for the future (2080) using the CCSA model. The descriptions of these steps are as follows: (Appendix 4.3.1 illustrated the map analysis)

Process 1

Input maps from Mulligan (1999) are: Potential native broadleaved woodland (*potwd*) and potential native broadleaved woodland for 2080 with low and high climate change scenarios (*nvc80l* and *nvc80h*) for the Snowdonia National Park (SNP). These maps described five different categories of land, indicating W4, W7, W9, W11 and W17 of national vegetation classes (NVC) as potential native broadleaved woodland (details are in Appendix 4.2.2). All the maps were reclassified into Boolean maps to show the potential native broadleaved woodland in the SNP (*potwdre*, *pnvc80l* and *pnvc80h*). Input maps of three selected sites (three scenarios of section 3.4.5) from chapter three are: *scnario1*, *scnario2*, and *scnario3*. The newly created Boolean map for the potential native broadleaved woodland (*potwdre*) was overlaid on three selected site maps to locate the potential native broadleaved woodland for the selected sites (the macro routines for this stage are described in section 4.3.2.10 of Appendix 4.3.2). Mulligan (1999) maps were generated from the macro described in section 4.3.2.1 to 4.3.2.9 (Appendix 4.3.2).

Process 2

The Boolean maps produced in process 1 stage for potential native woodland for 2080 with low and high climate change scenarios (p*nvc80l* and *pnvc80h*), were overlaid (multiply) with the three selected site maps (three scenarios of section 3.4.5) to generate maps with potential native woodland for 2080 considering low and high climate change. Hence, six maps (*kyosnp1l*, *kyosnp2l*, *kyosnp3l*, and *kyosnp1h*, *kyosnp2h*, *kyosnp3h*) were created for low and high scenarios.

Process 3

The maps created in process 2 were reclassified to create Boolean maps to show only the potential native woodland. The maps were with low and high climate change scenarios and named as *Rksnp1l*, *Rksnp2l*, *Rksnp3l* and *Rksnp1h*, *Rksnp2h*, *Rksnp3h*. These maps identify the soil classes of different scenarios when they are overlaid with fifteen distinct soil classes (*snpsol*) of the study area.

Process 4

Soil map of the SNP (*stsnsoil)* was used as an input map in this stage. This map was reclassified to show only fifteen distinct soil classes (*snpsol*) of the study area. Maps produced in Process1 and 3, were overlaid (multiply) with the soil class map (*snpsol*) to detect the soil classes for the potential native woodlands for the present and for 2080 with low and high climate scenarios. The new maps are: *Powsc1so*, *Powsc2so* and *Powsc3so* (for the present time), *Rksp1lso*, *Rksp2lso*, *Rksp3lso* and *Rksp1hso*, *Rksp2hso*, *Rksp3hso* with low and high climate change scenarios (for 2080) respectively.

Process 5

The area (in hectares) of suitable sites in every map of potential native broadleaved woodland with climate change scenarios (maps generated in process 2) and every soil class in accordance to the scenarios (maps generated in process 4) were calculated by the GIS function ***AREA***.

4.3.3.2 Estimating organic carbon for the selected sites

The total organic carbon (tree, litter and soil) of potential native broadleaved woodland for the present and the future (2080) of selected sites was estimated using the methodology presented in section 3.3.2. The map analysis and macro routines for the areas of the sites according to yield class and soil classes for three scenarios with high and low climate change are presented in Appendix 4.3.3.

4.4 Results

Presented here are: the performance of GIS functions in the simulation of the climate change scenarios adoption (CCSA) model, to locate the sites of potential native broadleaved woodland for the present and the future (considering high and low climate change scenarios for 2080), also estimating organic carbon sequestration if the area were replaced by native broadleaved woodland.

4.4.1 Integrating Mulligan's (1999) maps

4.4.1.1 Estimating the areas of potential native broadleaved woodland sites for the present time (2000) and climate situation

Three new maps (*Powsc1re*, *Powsc2re* and *Powsc3re*) were made by overlaying the map of potential native broadleaved woodland (Mulligan, 1999) for 2000 with the maps of selected sites (three scenarios of section 3.4.5) in the study area.

Powsc1re showed no suitable locations for PNBW for scenario1 from the organic carbon model (section 3.4.5). Table 4.4.1 shows the areas of potential native broadleaved woodland using the three scenarios. In the organic carbon model, only areas presently under conifer stands in the SNP were available. However, Mulligan's PNBW model considered all land which has some potential for supporting native woodland in the SNP.

Table 4.4.1 Suitable areas for potential native broadleaved woodland (present time) in the study area (sites located in three scenarios of section 3.4.5).

Selected sites	Oak YC	Land available in organic carbon model (hectare)	Land available as potential native broadleaved woodland (hectare)
Scenario1	YC 2	70	-
Scenario2	YC 4	6,029	1,054
Scenario3	YC 6	4,888	1,009
Total		**10,987**	**2,063**

Table 4.4.1 indicates that scenario 2 has higher land (6029 hectare) of organic carbon model than scenario3 but shows a lesser (proportionate) PNBW for the present time (2000). The reason may be scenario 2 of organic carbon model included a greater portion of peat soil (1667 hectares). On the other hand, Mulligan (1999) considered five NVC classes in his PNBW model with specific soil classes (Section 4.2.8) where peat soil was not considered as potential for stated NVC classes. So, peat soil areas were not included when overlaying the map of Mulligan's (1999) over scenario 2 of organic carbon model.

4.4.1.2 Estimating the areas of potential native broadleaved woodland sites for 2080 with high and low climate change scenarios

Six maps were generated by overlaying the maps of potential native broadleaved woodland for 2080 with high and low climate change scenarios (Mulligan, 1999) and selected sites (three scenarios of section 3.4.5) of the study area. The areas of suitable sites for potential native broadleaved woodland for 2080 with high and low climate change scenarios are presented in Table 4.4.2.

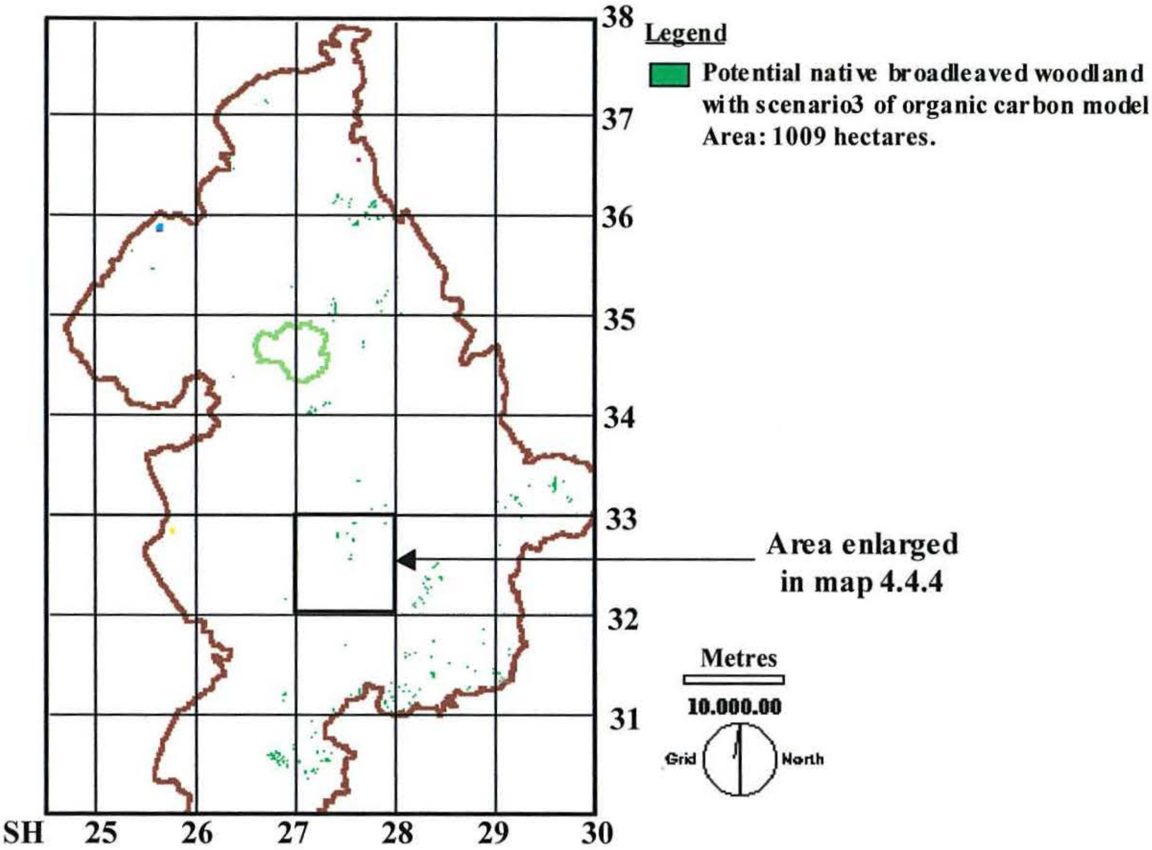
Table 4.4.2 Areas of suitable sites for potential native broadleaved woodland for 2080 with high and low climate change scenarios in the study area.

Selected sites	Land available with organic C model (hectare)	Potential native broadleaved woodland for 2080	
		High climate change scenario (hectare)	Low climate change scenario (hectare)
Scenario1	70	15	15
Scenario2	6,029	761	758
Scenario3	4,888	1,115	1,359
Total	**10,987**	**1,891**	**2,131**

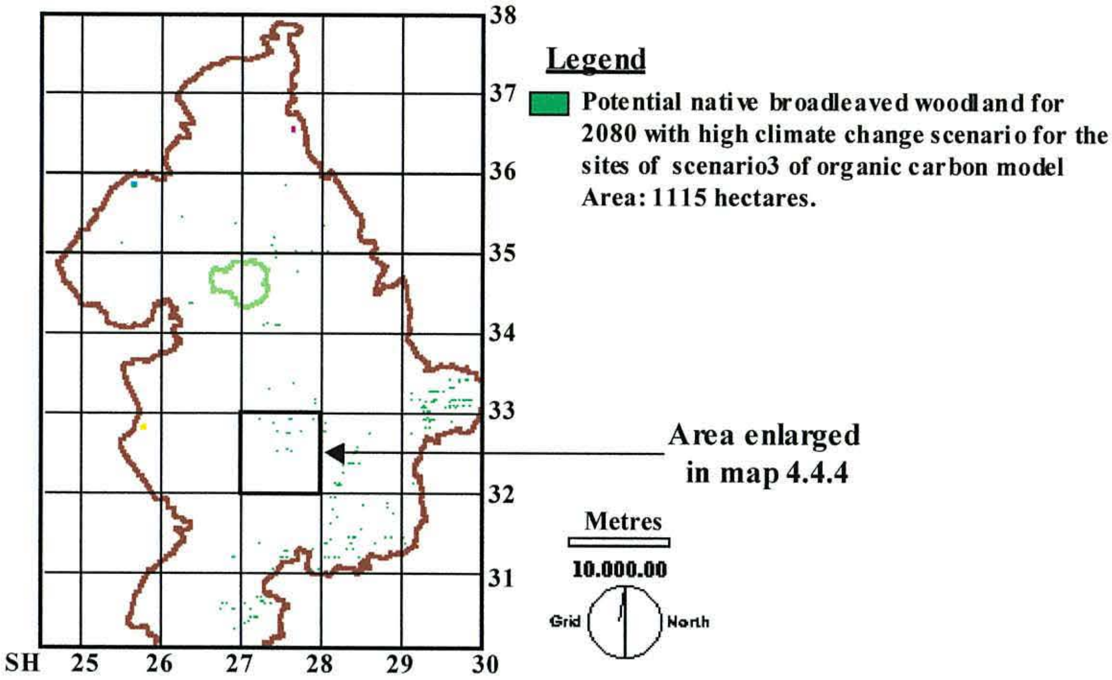
In Table 4.4.2 the potential sites for the native broadleaved woodland for 2080 with low climate change scenario (2,131 hectare) is higher than the high climate change scenario (1,891). The higher rise of temperature (3^0C) and precipitation (9%), in the high climate change scenario 2080, may not be suitable for some of the native woodland species for survival and development. In the 2080 high scenario may result in a bigger change (1,891ha – 2,063ha = -172 ha) than the low climate change scenario (2,131ha – 2,063ha = 68ha) from the present PNBW.

Map 4.4.1 shows the locations of PNBW with scenario 3 of organic carbon model for the present time (2000) and Map 4.4.2 and 4.4.3 demonstrate the locations of PNBW for 2080 with high and low climate change scenarios respectively.

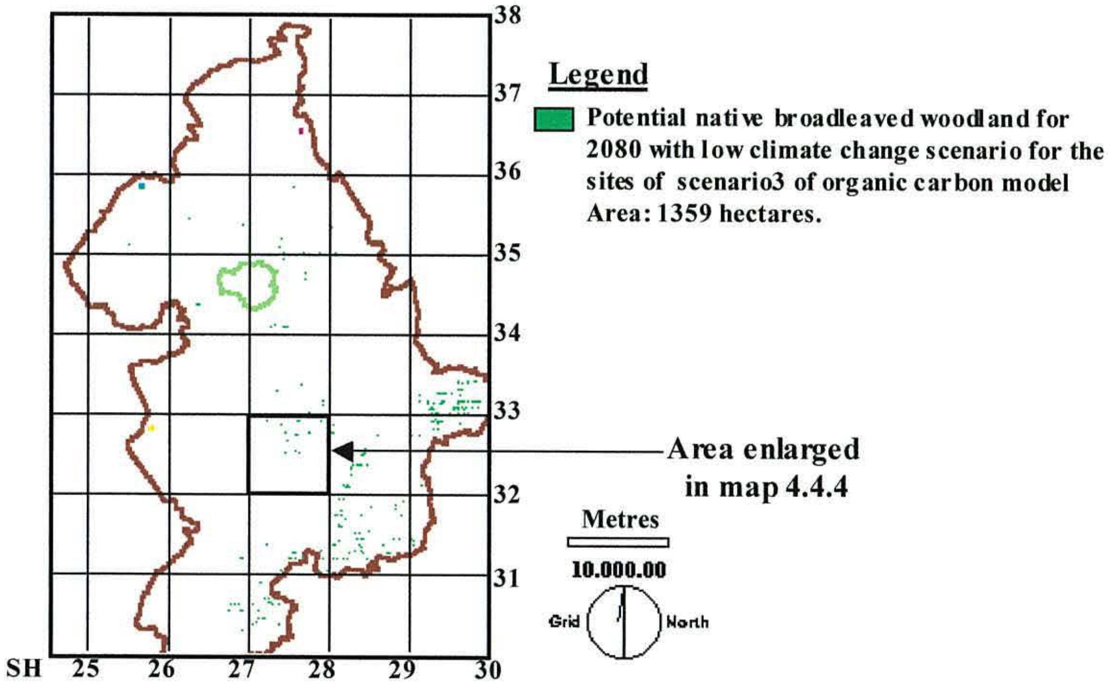
The details of a section of 10 km x 10 km of *Scenario2*, *Scenario3*, *Powsc2re*, *powsc3re*, *Kyosnp2h*, *Kyosnp2l*, *Kyosnp3h*, and *Kyosnp3l* maps is illustrated in Map 4.4.4. These enlarged maps show the different locations of sites between scenarios (2 and 3) of the organic carbon model, present and future (2080) potential native broadleaved woodland with high and low climate change scenarios.



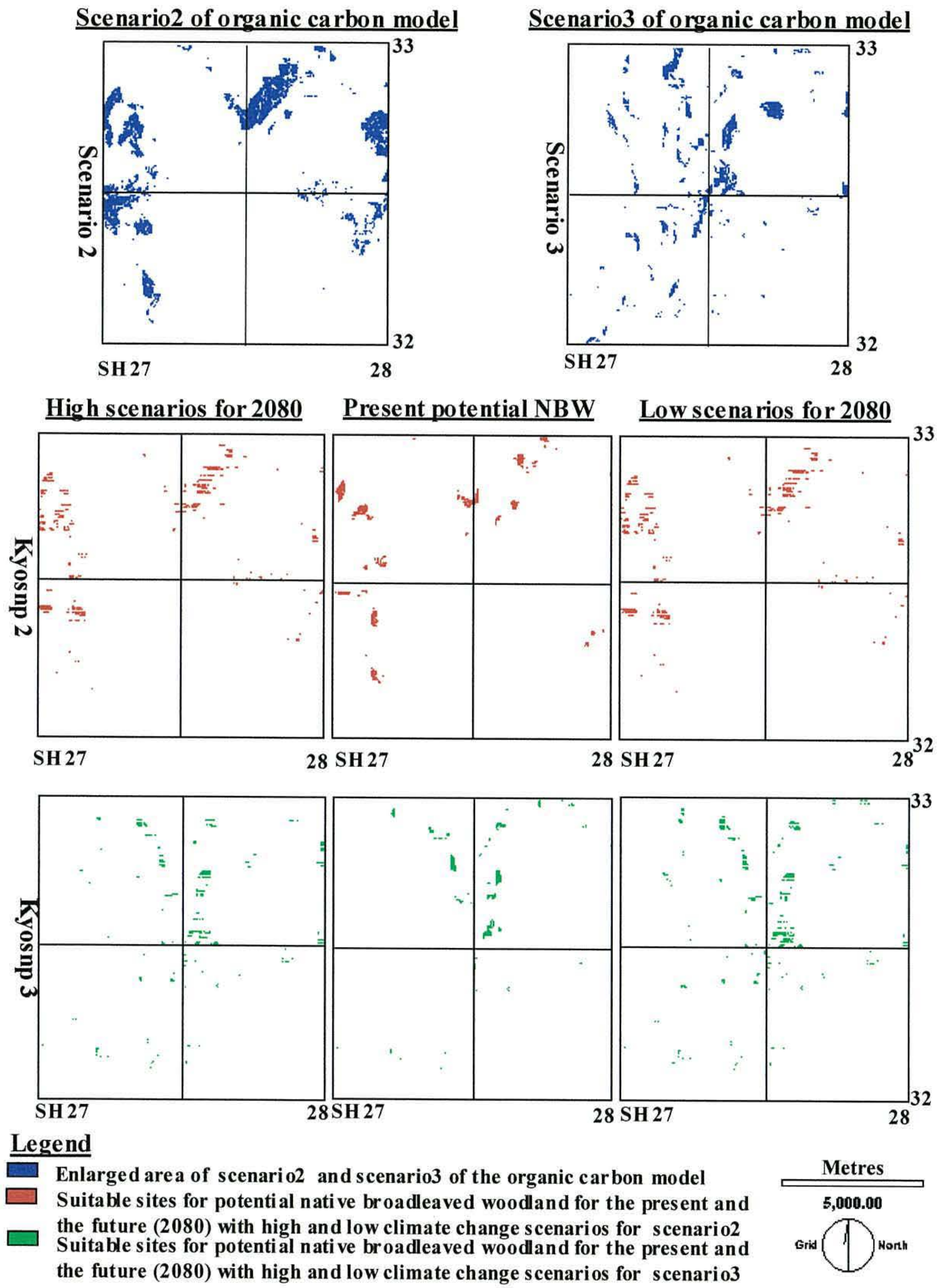
Map 4.4.1 Site locations of potential native broadleaved woodland (for 2000) for the sites of scenario 3 of section 3.4.5 (chapter three: organic carbon model).



Map 4.4.2 Site locations of the potential native broadleaved woodland (PNBW) for 2080 with high climate change scenario for the sites of scenario3 of section 3.4.5 with the CCSA model.



Map 4.4.3 Site locations of the potential native woodland (PNBW) for 2080 with low climate change scenario for the sites of scenario3 of section 3.4.5 with the CCSA model.



Map 4.4.4 Showing the differences between sites available in the enlarged area (10km x 10km) for scenario2 and scenario3 and potential native woodland for the present and the future (2080) with high and low climate change scenarios.

4.4.2 Effects of climate change on distribution of vegetation

The land distribution of the potential native broadleaved woodland for the present and for the future (2080) with high and low climate change scenarios for the sites of scenario2 and scenario3 of the organic carbon model (section: 3.4.5.2 and 3.4.5.3), according to altitude classes are presented in the following Table 4.4.3 (Macro and map analysis in Appendix 4.3.3).

Table 4.4.3 Land distribution according to altitude class for PNBW of the CCSA model with the sites of scenario2 and scenario3 of organic carbon model.

Altitude class metres	Potential native broadleaved woodland with Scenario2			Potential native broadleaved woodland with Scenario3		
	Powsc2re **2000 hectare**	***Kyosnp2h*** **2080 (high) hectare**	***Kyosnp2l*** **2080 (low) hectare**	***Powsc3re*** **2000 hectare**	***Kyosnp3h*** **2080 (high) hectare**	***Kyosnp3l*** **2080 (low) hectare**
< 200	-	-	-	-	7.25	11.00
200 - 250	10.00	44.75	44.75	-	128.25	180.75
250 - 300	581.00	131.00	130.75	42.75	148.75	203.00
300 - 350	196.75	177.00	177.00	604.25	162.25	220.00
350 - 400	246.25	150.50	149.00	183.00	184.00	220.25
400 - 450	20.00	94.75	93.75	169.50	262.25	286.00
450 - 500	-	79.50	79.5	9.75	170.50	180.50
500 - 550	-	46.25	46.25	-	43.25	47.00
550 - 600	-	27.00	27.00	-	6.75	7.75
600 - 650	-	7.00	6.75	-	0.25	0.75
650 - 700	-	1.75	1.75	-	0.25	0.25
700 - 750	-	0.25	0.25	-	-	-
750 - 800	-	0.25	0.25	-	0.75	0.75
800 - 850	-	0.50	0.50	-	0.25	0.25
850 - 900	-	-	-	-	-	-
> 900	-	-	-	-	0.25	0.25
Total	**1,054.00**	**760.50**	**757.50**	**1,009.25**	**1,115.00**	**1,358.50**

4.4.3 Estimating organic carbon for potential native broadleaved woodland

Six scenarios were found when the three scenarios presented in section 3.4.5 were tested with the CCSA model, using high and low climate change scenarios. Table 4.4.4 presents the estimated organic carbon accumulation of PNBW (assuming oak as the native broadleaf species) for the six scenarios for the future (2080) with high and low climate change scenarios (Appendix 4.3.3 and 4.4.1).

Table 4.4.4 Estimation of organic carbon sequestration for PNBW using the sites of three scenarios of section 3.4.5 with the CCSA model (details in Appendix 4.4.1) (h1, h2, h3: high and l1, l2, l3: low climate change).

Selected scenarios	Total area hectares	Tree organic carbon (tonnes)	Litter organic carbon (tonnes)	Soil organic carbon (tonnes)	Total locked organic carbon (tonnes)
Potential native broadleaved woodland for 2080 with CCSA model					
Kyosnp1h (h1)	15.00	503	300	1,613	2,415
Kyosnp2h (h2)	760.50	50,954	15,210	130,884	197,047
Kyosnp3h (h3)	1,115.00	104,810	22,300	240,346	367,456
Total	**1,890.50**	**156,266**	**37,810**	**372,842**	**566,918**
Kyosnp1l (l1)	15.25	511	305	1,640	2,456
Kyosnp2l (l2)	757.50	56,409	15,150	130,359	201,918
Kyosnp3l (l3)	1,358.50	127,699	27,170	278,993	433,862
Total	**2,131.25**	**184,619**	**42,625**	**410,992**	**638,236**

However, currently all the sites of the scenarios presented in section 3.4.5 are under conifer plantations. The differences of the organic carbon fixation between PNBW with the CCSA model and conifer plantation (81,366 tonnes with low and 71,410 tonnes with high climate change) for those sites are shown in Table 4.4.5. About 10,000 tonnes of more organic carbon would be stored with low than high climate change scenarios if all the areas of the scenarios were replaced with oak.

Table 4.4.5 Illustrates the differences in locking organic carbon by the different scenarios of PNBW / CCSA models and conifer plantations (details in Appendix 4.4.1 and 4.4.2).

CCSA scenarios	Area (hectares)	PNBW (tonnes)	Conifer (tonnes)	(PNBW-Conifer) organic carbon fixation	
				(tonnes)	% increase
a	b	c	d	f = c-d	g = (f/d) x 100
Kyosnp1h	15.00	2,415	1,837	578	14%
Kyosnp2h	760.50	197,047	177,496	19,551	
Kyosnp3h	1,115.00	367,456	316,175	51,281	
Total	**1,890.50**	**566,918**	**495,508**	**71,410**	
Kyosnp1l	15.25	2,456	1,872	584	15%
Kyosnp2l	757.50	201,918	176,946	24,972	
Kyosnp3l	1,358.50	433,862	378,052	55,810	
Total	**2,131.25**	**638,236**	**556,870**	**81,366**	

4.5 Discussion

This part of the study presents the discussion on:

- the GIS simulated climate change scenario adoption (CCSA) model and its workability to identify potential native broadleaved woodland (PNBW) for the future;
- an estimate of organic carbon sequestration for the identified sites of future (2080) potential native broadleaved woodland with high and low climate change scenarios.

4.5.1 Identifying the potential native broadleaved woodland

The accuracy in identifying the sites of PNBW greatly depends on Mulligan's (1999) maps and the input maps assembled in this study.

Potential native broadleaved woodland (PNBW)for the present time (2000)

Powsc1re, Powsc2re and *Powsc3re* (example: Map 4.4.1) were the resultant maps demonstrating suitable sites for PNBW (for the present time: 2000) in the study area (scenarios: 1-3 of section 3.4.5). No suitable sites for native broadleaved woodland were found in the map for scenario1 (*Powsc1re*). However, Table 4.4.1 presented the suitable PNBW with the sites of scenario2 and 3 of the organic carbon model (*Powsc2re* and *Powsc3re*), as 1054 and 1009 hectares respectively.

Potential native broadleaved woodland for the future (2080) with climate change scenarios

Table 4.4.2 showed the PNBW for the future (2080) with scenario2 (*Kyosnp2h* and *Kyosnp2l*). Although scenario2 of the organic carbon model covered more sites (6029 ha) than the other scenarios (70 and 4888 ha with scenarios 1 and 3 respectively), the CCSA model produced suitable sites under scenario2: 761 hectares and 758 hectares which were less than those of scenario3 (*Kyosnp3h* and *Kyosnp3l*): 1115 hectares and 1359 hectares. Scenario2 of the organic carbon model (chapter three section 3.4.5) incorporated a greater portion of peat soils but Mulligan (1999) didn't include peat soil as potential for PNBW in his map. When overlaying the map of PNBW for the Snowdonia National Park (Mulligan, 1999) on the map of scenario2 of the organic carbon model, sites on peat soils (1667 hectares in scenario2: chapter three) were not included in the PNBW for the scenario2 (*Powsc2re*).

Map 4.4.1 (*Powsc3re*) showed the PNBW sites for the present time (2000) considering the areas covered in scenario3 of organic carbon model (section 3.4.5). Applying the CCSA model for the sites of scenario3, Map 4.4.2 (with high scenario: *Kyosnp3h*) and Map 4.4.3 (with low scenario: *Kyosnp3l*) were generated to locate sites of the PNBW for future (2080). Similar maps were produced for scenario1 and scenario2 of the organic carbon model. The enlarged sections of 10 km x 10 km maps of PNBW presented in Map 4.4.4 for the present and the future (2080) high and low scenarios demonstrate different locations for the sites of PNBW. Although the maps were generated from the same sources (scenario2 and scenario3 of section 3.4.5), this demonstrates how vegetation distribution may be very sensitive to future climate changes.

4.5.2 Effects of climate change on distribution of PNBW

The sites of PNBW which have the potential to fix the same or more organic carbon than the conifer in the organic carbon model (scenarios in section 3.4.5) are not same in the future under climate change scenarios (Table 4.4.2). The change in suitable sites for woodland in the future resulting from climate change effects may be due to the following reasons:

Suitable soil class

Mulligan (1999) selected some soil types for NVC woodlands: W4, W7, W9, W11 and W17 (details are in section 4.2.8). Scenarios 1, 2 and 3 of the organic carbon model (section 3.4.5) are also based on selected soil types. Those scenario sites matched with the soil types of Mulligan (1999) are suitable for the potential native broadleaved woodland. Therefore, soil class acts as one of the basic criteria for selecting the sites of PNBW for the Snowdonia National Park.

Altitude, soil moisture and temperature

The CCSA model used the high and low climate change scenarios of UKCIP 1998 *i.e.* 3^0C increase as high scenario and 1.1^0C increase with low scenario for 2080. Mulligan (1999) used a lapse rate of 0.6^0C (Wheeler and Mayes, 1997; Woodward and Pigott, 1975) for each increase of 100 m altitude. Considering these two phenomena in the CCSA model performance, Table 4.4.3 showed the distribution of PNBW for the present (2000) and the future (2080) with altitude classes in the study area (scenarios 2 and 3 of organic carbon model: section 3.4.5).

Suitable sites for the PNBW (present time) may be available within the altitude limit 200 metres to 500 metres for the sites of scenario2 (*Powsc2re*) and scenario3 (*Powsc3re*) of the organic carbon model. On the other hand, suitable sites for the PNBW for the future (2080) considering high and low climate scenarios may be available from altitude classes below 200 metres to over 600 metres. Table 4.4.3 indicated that suitable sites for plant communities in the future might be different from their existing (present) sites. Woodward (1987) also agreed that there is a significant difference in the presence of species in relation to altitude. Furthermore, CCRIG (1996) indicated that a 1.5^0C increase in mean annual temperature would cause an altitude shift of 40-50 metres per decade. This means that the plant communities presently at 200 metres altitude may find suitable sites at up to 600 metres elevation by 2080 (eight decades). Vegetation communities presently at 450 metres may find suitable sites up to 850 metres by 2080.

The following Figure 4.5.1 shows the pattern of availability of suitable sites for plant communities. The suitable sites for vegetation were found towards higher altitudes using the high and low climate changes of scenario3 with the CCSA model (Figure 4.5.1). A sharp decline of available land for PNBW with high and low climate change scenarios is found above 450 metres in Figure 4.5.1. This may happen due to a lack of suitable conditions for natural colonization for seedling establishment, but mainly due to the small land area above 450 metres in altitude.

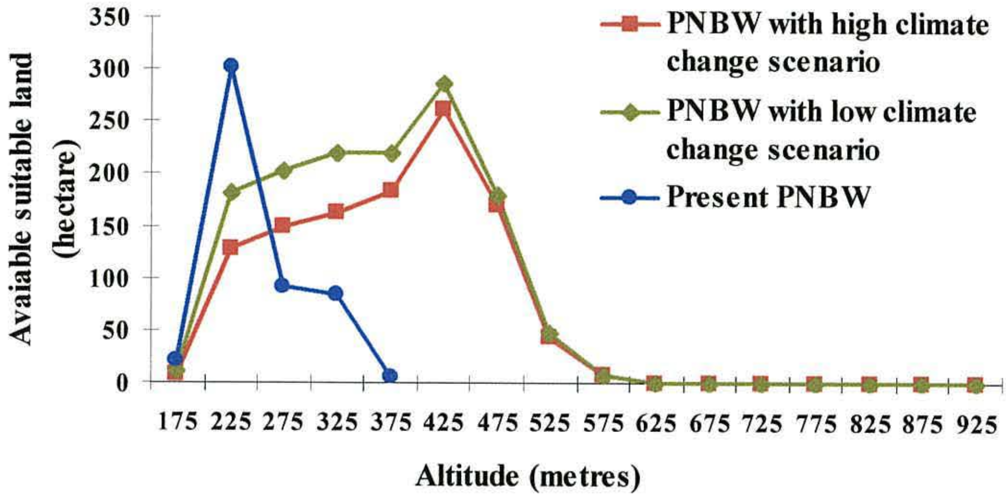


Figure 4.5.1 Showing the distributions of land available for potential native broadleaved woodland (PNBW) in the present and the future (scenario3) with altitude. Data presented in Table 4.4.3.

The sites for PNBW of the CCSA model considering high and low climate change scenarios showed a distribution of vegetation from 200 metres to 900 metres altitude (Table 4.4.3). This revealed that some plant communities may not find suitable climatic conditions to survive (at their existing elevations) and with natural colonization processes they may find their ideal climatic conditions at a higher altitude. This may be due to the fact that temperature would go up (3^0C with high and 1.1^0C with low climate change scenarios) in coming decades and temperature decreases with altitude. Some plant communities may migrate in the warmer future climate and shift from lower altitudes to higher cooler ones. This is supported by Woodward (1987) whose study showed a strong positive correlation between seed germination and increased temperature. For uplands, wind pushes the air mass with saturated moisture towards a higher altitude, and with temperature decline, the air mass is condensed until it comes down as precipitation. After precipitation the area is warmer and the rest of the moisture in the air will flow towards a higher elevation. High wind velocity at a higher altitude may be another reason to evaporate the soil moisture. This approach was agreed by Dhubhain (1998), where he mentioned a 13% increase of wind velocity with an increase of 100 metre altitude in a tatter flag study of Scotland (data produced by Miller *et al.*, 1987). This may retard the germination of seeds and the natural process of seedling establishment. Figure 4.5.1 shows that less sites of PNBW (potential native broadleaved woodland) are available with an altitude of more than 450 metres.

4.5.3 Organic carbon sequestration with future PNBW

Tree, soil and litter organic carbon sequestrations for the sites of future PNBW considering climate change scenarios were estimated. A similar approach was taken to estimate organic carbon in relation to forest and climate change by Joyce *et al.* (1995).

Although the scenarios of section 3.4.5 of chapter three described the sites that would fix as great an amount of carbon stock as conifer if they were replaced by native broadleaved woodland, the suitable PNBW sites and the estimated organic carbon are changed in the CCSA model. Table 4.4.4 showed the estimated organic carbon for the sites of the future PNBW with climate change scenarios. The results (Table 4.4.4) revealed that PNBW under the low scenario for 2080 (638,236 tonnes) would sequester more organic carbon than PNBW under the high scenario for 2080 (566,918 tonnes). This is because of more land available under low than high climate change scenarios. This may mainly happen due to the reduced land available at higher elevations (cooler region). However, all the sites for these scenarios are currently under conifer plantations. Table 4.4.5 showed the overall increase (in percentage) of organic carbon fixation for the future if oak replaces the conifer. Table 4.4.5 also showed that with high climate change scenario a total of 71,410 tonnes (14%) and with low climate change scenario a total of 81,366 tonnes (15%) more organic carbon will be fixed if conifers were replaced by oak. The following Table 4.5.1 illustrates the areas of suitable sites for the PNBW for the future (2080) and the scenarios presented in the organic carbon model of section 3.4.5. The table shows that smaller land areas for potential native woodland may be available in future under low and high scenarios than the land may be potential for replacing conifer by oak (organic carbon model) considering carbon sequestration.

Table 4.5.1 Areas of suitable sites for the organic carbon model and the CCSA (2080) model.

Organic carbon model	Site areas hectares	CCSA model (High)	Site areas hectares	CCSA model (Low)	Site areas hectares
Scenario1	70	Kyosnp1h	15	Kyosnp1l	15
Scenario2	6,029	Kyosnp2h	761	Kyosnp2l	758
Scenario3	4,888	Kyosnp3h	1,115	Kyosnp3l	1,359
Total	**10,987**		**1,891**		**2,131**

4.5.4 Kyoto – consistent forest and potential native broadleaved woodland

At Kyoto the UK agreed to reduce greenhouse gas emission to 8% below the 1990 level (which means a reduction of 0.0127 gigatonne C per year), but with the European Union (EU) it accepted a target of 12.5%, and for domestic purposes the target is 20% below the 1990 levels by 2010 (DETR, 2000; Cannell *et al.*, 1999). These targets lead the UK to aim for more organic carbon sequestration in the short and the long term. Foresters may maximise organic carbon production from the same land using their management skills and technology. Kyosnp1, 2 and 3 scenarios (high and low) of the CCSA model with oak may sequester more organic carbon (Table 4.4.5) than conifer and would also be suitable under future climate change.

Sites with CCSA scenarios: Kyosnp1-3 (high and low), have the potential for future native broadleaved woodland with respect to organic carbon sequestration. Natural regeneration is found where areas are protected from grazing in the Snowdonia National Park. Tracy (1999) reported a significant adverse effect of grazing on native woodland establishment and development. Data on oak seedling establishment in conifer plantations in the Snowdonia National Park (study area) were not available. From field visits it is known that in any area which is protected from grazing, there may be ample opportunity for natural colonisation of native species. The following Photograph 4.5.1 shows how profuse seedlings of birch and other native species colonise the gaps in conifer plantations.

Photo 4.5.1 Profuse regeneration of birch and other native broadleaves in gaps in an upland conifer forest. (Photo: J. H. Williams).

A picture may be worth a thousand t tests (Cooper and Zangwill, 1989)

4.5.5 Macro routine for CCSA model

The climate change scenario adoption (CCSA) model was used with the IDRISI macro language (Appendix 4.3.1). Mulligan's (1999) maps were also generated using the macro languages of his model. The CCSA model used here was a combination of the Mulligan (1999) climate change model and an adaption of climate change scenarios for a specific land use. The model uses different functions of GIS: for Boolean constraints: ***reclass***; for decision-making: ***multi criteria evaluation*** (***MCE***); for data compilation: ***overlay***; to calculate the area of a map with respect to its attributes: ***area***; and to see cross-reference of data: ***crosstab***. Macro routines can be used to update the data when required.

4.5.6 Limitations of the CCSA model

The maps from Mulligan (1999) showing potential native broadleaved woodland of the Snowdonia National Park for the present and the future (2080) were overlaid on the maps of scenario1, 2 and 3 of the organic carbon model (section3.4.5) in the CCSA model. The accuracy and the performance of the CCSA model greatly depended on these two sets of maps. The landuse data of the study area to generate these maps were from the 1990s, so any harvesting or newly planted areas in the study sites were not included. Mulligan's models used temperature and precipitation to generate climate change scenarios, but did not include other climatic variables such as wind, sunlight, relative humidity *etc.* which may have an effect on vegetation distribution.

4.6 Summary of the chapter

A macro-language-based GIS model is proposed as an effective tool to show how climate change scenarios of UKCIP 1998 will be adopted as a decisive factor in forest management, such as replacing exotic conifers with native broadleaved woodland. The proposed climate change scenario adoption (CCSA) model incorporated the maps of potential native broadleaved woodland (PNBW) for the present (2000) and the future (2080) using the climate change models of Mulligan (1999). The suitable sites for PNBW, within the areas (10,987 hectares: organic carbon model) which are presently with conifer and enable to lock more organic carbon than conifer if they were replaced by oak (section 3.4.5), for present and future (2080) climate change scenarios were located by overlaying Mulligan's (1999) maps with the maps of three scenarios presented in the organic carbon model (section 3.4.5). The organic carbon sequestered with the stated future PNBW with high and low climate change scenarios for 2080 was also estimated.

The results revealed that less suitable land for PNBW might be available in the future (2080) under high (1891 hectares) than low (2131 hectares) climate change scenario. It may due to increase of temperature (with high 3^0C and low 1.1^0C) in future where plant communities may need cooler regions for seedling establishment and small land area may available in higher altitude (cooler area) in the study area. The result also depicted that more organic carbon (10,000 tonnes) would be stored under the low (81,000 tonnes) than the high (71,000 tonnes) climate change scenarios for 2080 if the conifer were replaced by oak.

CHAPTER FIVE
THEME TRANSFER TO BANGLADESH

5.1 Role of spatial datasets in the forest management of Bangladesh

The main objective of this chapter was to show the possible application of the models that were developed in this piece of research in the forest management of Bangladesh. To fulfil the main objective, the following specific objectives (Figure 5.1 shows the flow of potential application of models) were set:

- to show a possible way to demonstrate the role of spatial data integration in generating a wind composite model for the hill forests of Bangladesh;
- to clarify the possible applications of the organic carbon model with spatial datasets for constructing yield class and estimating organic carbon for the hill, coastal plantations and mangroves of Bangladesh;
- to illustrate the potential use of climate change scenarios adoption (CCSA) models for mangroves, coastal and parts of hill forests of Bangladesh.

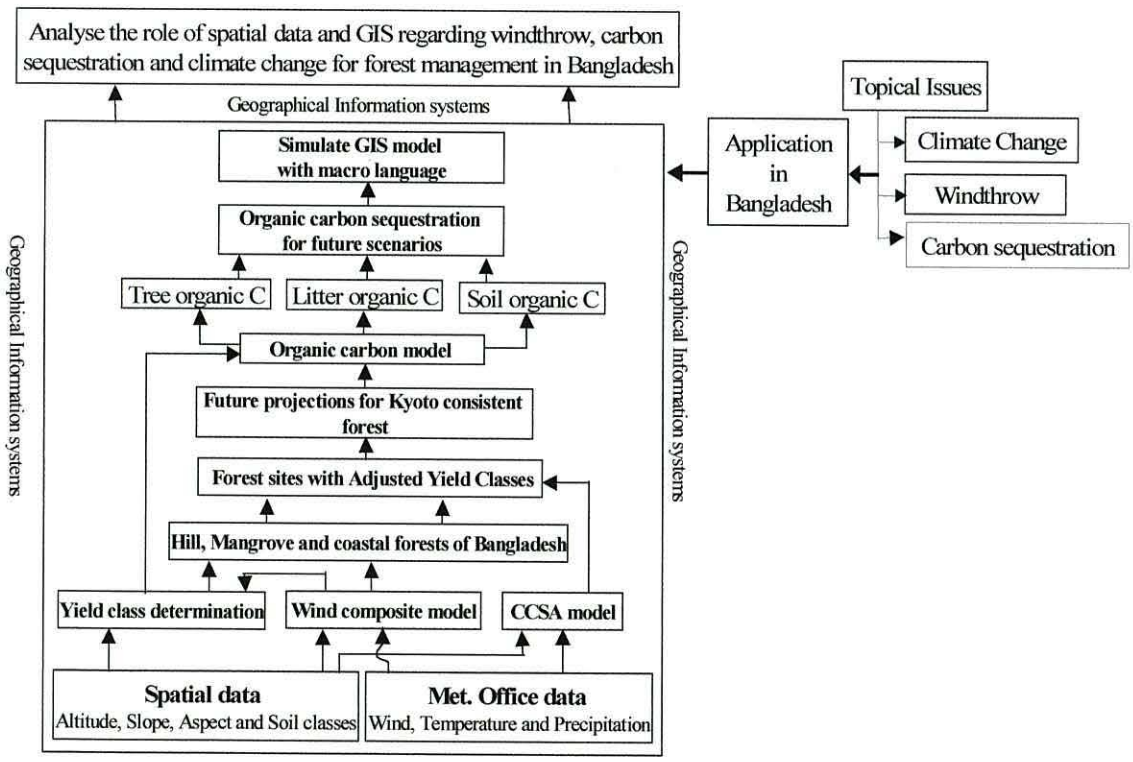


Figure 5.1 Demonstrates potential applications of the wind composite, organic carbon and CCSA models for the forest management of Bangladesh.

5.2 Bangladesh and her forest resources

5.2.1 Location

Bangladesh is a South Asian country situated between $20^0 34'$ and $26^0 38'$ north latitude and between $88^0 01'$ and $92^0 41'$ east longitude (Map 5.1) with an area of 147,570 square kilometres (sq. km) (BBS, 1999) and a population of 126 million (World Bank, 2000). The country is bordered by India in the north, north-east and west; Myanmar in the south-east and the Bay of Bengal lies in the south.

5.2.2 Climate

The climate of Bangladesh is tropical humid and warm with three main seasons: a hot summer with rainfall (March to June), a hot and humid monsoon with heavy rainfall (June to October) and a relatively cooler and drier tropical winter (November to March). Annual average temperature ranges from 19^0C to 29^0C and annual rainfall ranges from 1,250 mm in the west to 2,500 to 5,000 mm in the north-west (World Bank, 2000). Humidity is high throughout the year; June to September above 80% and the least humid months are January, February and March (below 58%) (Rashid, 1991). Wind directions change with the season, but in October the winds are very variable with a definite strengthening of the northerly winds at the expense of the south easterly (Rashid, 1991).

Bangladesh suffers from climate dependent hazards such as riverine and coastal floods, tropical cyclones and drought. In the last decade, a tropical cyclone in April 1991 (wind speed 225 km/hour with tidal surges over seven metres high) caused about 138,000 deaths (Haider *et al.*, 1991) and the 1998 flood (which is termed as the worst in the century), inundated two thirds of the country and washed out development efforts, crops, physical infrastructures and assets of over US$ 2.5 billion as well as causing hundreds of death (World Bank, 2000).

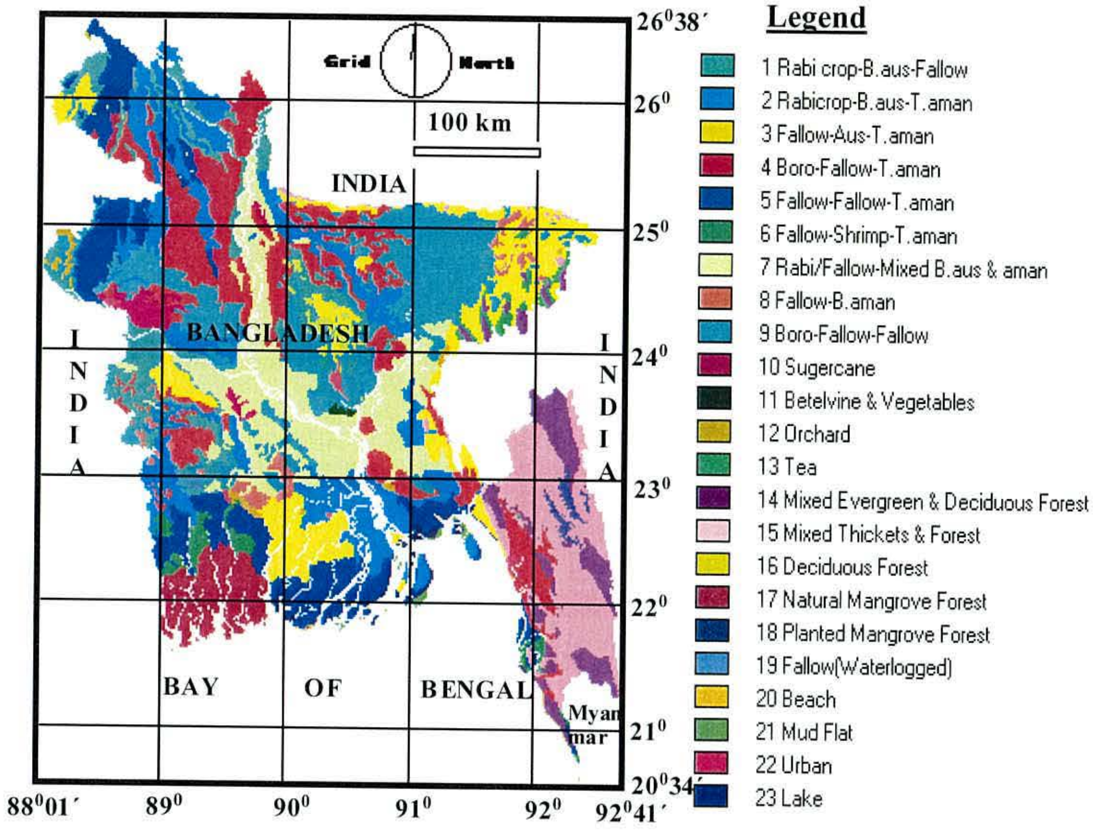
5.2.3 Land use and forest resources

Map 5.1 presents detailed land uses of Bangladesh mainly with agriculture, and forestry. Agricultural land makes up 64.2%, forest lands account for 17.8% and urban, water and others make 18% of the area. Physical cover of the forest land of Bangladesh is illustrated in the following Table 5.1. A forest cover map of Bangladesh (Map 5.2) is produced by reclassifying land use Map 5.1.

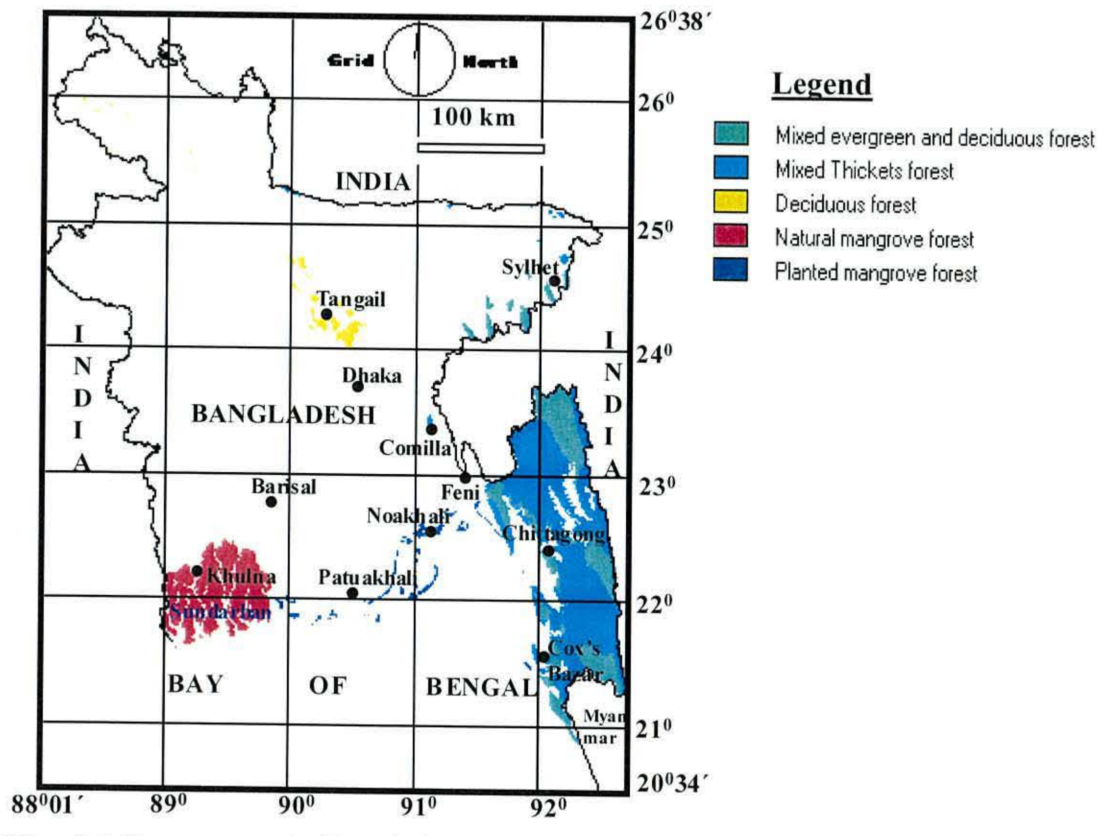
Table 5.1 Physical cover of forest land of Bangladesh (ADB, 1993)

Type of land cover		**Area**
Productive	***Natural forest***	**Hectare**
	Medium – good density	460,700
	Poor density	82,200
	Bamboo	71,200
	Scattered trees or Barren	95,900
	Total	**710,000**
	Plantations	303,100
	Jhummed or Encroached	111,000
	Total	**1,124,100**
Unproductive	**Unproductive (completely)**	12,900
	Parks or Sanctuaries	116,700
	Water	90
	Unclassified State Forests	98,8510
	Total	**1,118,200**
Grand total		**2,242,300**

Tropical evergreen and semi evergreen hill forests of about 1.4 million hectares are mostly located in the eastern hills: 52 tree species are naturally found (Das, 1990). At present, 0.97 million hectares of land is denuded as a result of shifting cultivation, illicit felling, accelerated soil erosion and uncontrolled fire hazard. Tropical littoral (13 tree species; Das, 1990) and swamp forests (12 tree species; Das, 1990) covering 0.67 million hectares are situated in the south and south–western deltaic zone, locally known as *Sundaerban* (habitat of the Royal Bengal Tiger). Tropical moist deciduous forest covers 0.12 million hectares of land over the inland plains with the dominant species sal (*Shorea robusta*) (Rahman, 1995).



Map 5.1 Land uses of Bangladesh (Adapted from SRDI, 1996)



Map 5.2 Forest cover in Bangladesh (Extracted from SRDI, 1996)

5.3 Rationale for technological intervention in the forest management of Bangladesh

State owned forests of Bangladesh are managed with the *Working plan* which is practically a management plan for 10 years to manage forest areas under a forest division. Scientific management of the forests of Bangladesh has been ongoing since 1917. Huge historical data sets were evolved with this process, which may be strong back up information for any modeller to draw a forest management prescription. Furthermore, the meteorological information can be brought together from different stations situated in the pocket of the forest areas of Bangladesh and might have the potential to generate climate change scenarios for the future on a local basis. Moreover, good databases especially concerning climate have been developed by different international and national research organisations such as the Meteorology department, SPARSSO (Bangladesh Space Research and Remote Sensing Organization), different development projects of the forest department (FRMP, ARMP), the Bangladesh forest research institute (BFRI), universities, the flood action plan (FAP), the World Bank, the Asian Development Bank (ADB) and development projects of the United Nations.

ADB (1993) identified the following seven main drawbacks of Bangladesh forest management: a serious gap between forest product supply and demand, unsustainable management practices in natural forests, increasing deforestation and afforestation rates, low net productivity and utilization, unreliable data, lack of participation and benefit to local people and poor service conditions for departmental staff. ADB (1993) also pointed out that forest plantations in Bangladesh show disappointing results (low production), considering its net timber yield per hectare by regional and international standards; while depicting also that the felling of natural forests for commercial use, followed by plantations, is not sufficient justification for such action.

The Forestry Master Plan (FMP) for 1993-2012 produced three scenarios (ADB, 1993; ADB, 1994). The first one is business as usual or *status quo*, then second one signifies low development potential as it depicts only adding money and manpower but retains practices and policies of forest management. On the other hand, the third has high development potential and incorporates new technologies, practices and policies.

Despite this situation, the Bangladesh Forest Department recently established a GIS cell to create a database for its forest areas. Spatial data for forests are available now in the form of aerial photographs (only for some forest areas), hard (Paper) maps and in record keeping sheets (maintained by the field office). All the sources of data can be brought together to create a GIS database for the forests of Bangladesh. Hence, this database is a very effective resource for the policy makers or planners.

The time has come to organise the data sets from different sources and utilise them with the concerned vision of the forest manager from a national level to a regional or local scale, in order to create and manage forests which are internationally consistent, nationally viable and adaptable to future climate change *i.e. Kyoto-consistent forests* for the future.

5.4 Application of generated models in Bangladesh

5.4.1 Applying the wind composite model for Bangladesh forests

The existing situation

A forest is an unlocked resource which always carries risks, on the one hand from human beings and on the other hand from climate. The hill forests of Bangladesh are heavily encroached by local people because of shifting cultivation (Hall and Uhlig, 1991), for agricultural land, pilferage of forest produce for local consumption and trade in a large and expanding population (Al-Amin, 1989; Al-Amin *et al.*, 1989). Natural calamity is always a companion of Bangladesh forests. Bangladesh is particularly vulnerable to tropical cyclones (Table 5.2); the combined effect of intensely low atmospheric pressure, extremely strong winds and high tides causes a surge of water which can reach far inland. In one of the worst of such disasters in the last century over 250,000 people were drowned in

Bangladesh in 1970. The people of the country experienced similar cyclones in 1991, and smaller surges are a regular occurrence there (Houghton, 1994). Table 5.2 illustrates the major affected areas of strong winds and cyclones and Map 5.2 illustrates the corresponding forests: such as hill forests in Chittagong and Cox's Bazar, coastal forests in Noakhali, Khulna, and Patuakhali.

Table 5.2 Major cyclonic storms with maximum wind speed from 1981 to 1998 in Bangladesh (BBS, 1999).

Date of occurrence	Max wind speed (Km/hr)	Affected areas in Bangladesh
10-12-1981	120	Offshore islands and char of Khulna, Barisal and Patuakhali
(14-15)-10-1983	93	Chittagong and Noakhali and their offshore islands and char areas
(5-9)-11-83	136	Chittagong, Cox's Bazar, Noakhali, Khulna, Barisal and Patuakhali and islands
(24-25)-05-1985	153	Chittagong, Cox's Bazar, Noakhali and their offshore islands.
(08-09)-11-1986	110	Chittagong, Noakhali, Patuakhali and Barisal and their offshore islands.
(24-30)-11-1988	160	Khulna, Jessore, Kustia, Barisal, Faridpur and their offshore islands
(25-29)-04-1991	225	Chittagong, Cox's Bazar, Noakhali, Khulna, Barisal and Patuakhali
31-05-91 to 02-06-91	110	Chittagong, Noakhali, Barisal and Patuakhali and their offshore islands
(17-19)-05-1992	90	Offshore islands and chars of Chittagong and Cox's Bazar
(17-21)-11-1992	50	Offshore islands and chars of Cox's Bazar
29-04-94 to 03-05-1994	210	Offshore islands and chars of Cox's Bazar
(21-25)-11-1995	210	Offshore islands and chars of Cox's Bazar
(7-8)-05-1996	56	Offshore islands and chars of Cox's Bazar
(26-29)-10-1996	75	Sundarban coast
(16-19)-05-1997	220	Offshore islands and chars of Cox's Bazar, Chittagong, Noakhali and Bhola
(25-27)-09-1997	150	Offshore islands and chars of Cox's Bazar, Chittagong, Noakhali and Bhola
(16-20)-05-1998	120	Offshore islands and chars of Cox's Bazar, Chittagong, and Noakhali
(19-22)-11-1998	90	Offshore islands and char of Khulna, Barisal and Patuakhali

Application

A wind composite model shows the integration of spatial data and techniques to generate a wind-risk assessment model, as for the UK uplands. The model itself is an application of the detailed aspect method of scoring (DAMS) where spatial factors, such as altitude, aspect and funnelling effects are combined with the wind and forest dynamics over a forest area (patch).

A similar type of model may be very useful for the forest areas which are vulnerable to windthrow in Bangladesh. However, the vision of ForestGALES (Forestry Commission, 2000) incorporated with FRAGSTATS within a GIS framework may be a good transferable technology to identify the wind prone forests of Bangladesh. The tatter flag system of wind data collection (Raynard and Low, 1984), particularly to determine the wind effects on topographical exposure, may be another potential method to apply in forests of Bangladesh to collect spatial datasets for the wind composite model.

Moreover, the same nature of hazards, such as fire, flood and other hazards related with climate change for a forest area, can be brought together to make a future plan for forest management.

5.4.2 Applying the organic carbon model for Bangladesh forests

The Forestry Master Plan (1993-2012) of Bangladesh identified three major set-backs in forest resource pricing, these are: a) Inefficiency b) out of date valuations c) direct government price setting or the indirect effect of highly priced inputs (ADB, 1993). Moreover, the plan identified the reasons for continued imbalances in resource values as being ineffective, irregular and unsystematic resource estimation and valuation. In fact, the existing pricing system is tantamount to subsidising forest products which encourages the fastest exploitation of those products (ADB, 1994). Proper estimation and quantification of forests goods and benefits are also necessary considering the three stated setbacks. The emitted carbon from Bangladesh to the atmosphere is described in Appendix 5.4.1.

Carbon released from the closed forests of Bangladesh was about 0.001 gigatonne in 1980 (Hall and Uhlig, 1991). Flint and Richards (1991) presented a historical scenario about carbon sequestration by vegetation of Bangladesh forests (Table 5.3) from 1880 to 1980.

Table 5.3 Total carbon content in vegetation in Bangladesh from 1880-1980 (Flint and Richards, 1991).

Country	Area (million hectares)	Total carbon content (gigatonne)			
		1880	**1920**	**1950**	**1980**
Bangladesh	14.80	0.00212	0.00177	0.00148	0.00109

Organic carbon estimation procedure may quantify intangible benefits (such as carbon sequestration) and provide an international parameter of weighting forest resources. The organic carbon model is a combination of GIS and spreadsheet analysis. The yield class estimation procedure using GIS needs soil, slope, altitude and exposure maps and the spreadsheet analysis quantifies the organic carbon stocks in accordance to yield class. However, an organic carbon model for the forests of Bangladesh needs:

- A model for estimating tree organic carbon stock (like the *Willis-Price* model) in accordance to species and yield classes, or yield tables for the species concerned (then the yield is converted into organic carbon stock with its maximum mean annual increment).
- Litter organic carbon can be evaluated from published sources preferably with respect to Bangladesh.
- Soil organic carbon with one-metre depth can be estimated as prescribed in the model.

5.4.3 Application of the climate change scenario adoption (CCSA) model

Climate change scenarios and Bangladesh

Table 5.4 shows the following climate change scenarios for 2030 and 2050, compared to the 1990 level with an average winter temperature: 19.9^{0}C precipitation: 12 mm per month and average monsoon temperature: 28.7^{0}C, precipitation: 418mm per month (World Bank, 2000).

Table 5.4 Climate change scenarios for Bangladesh (World Bank, 2000).

Year	Sea level rise (cm)	Temperature increase (^{0}C)		Precipitation fluctuation (%)	
		Monsoon	Winter	Monsoon	Winter
2030	30	(+) 0.7	(+) 1.3	(+) 11	(-) 03
2050	50	(+) 1.1	(+) 1.8	(+) 28	(-) 37

According to the latest study for Bangladesh (World Bank, 2000) the potential impacts due to climate change (in brief) are the following:

More precipitation in the monsoon season (for 2050) with higher temperatures

- Flood increases
- Increases in runoff with sea level rises increasing the flood area

Less precipitation in the winter season (for 2050) with higher temperatures

- Drought increases
- (-) 9% precipitation reduces runoff alarmingly and there would be no wheat cultivation in the south central and south west of the country

Sea level rise (for 2050)

- 4% of the land would be under sea level, which estimates that 6300 km^2 land will go under water, specially coastal districts will be more susceptible, reducing crop land in a land hungry country. Land loss with an increasing population (current rate 1.6% per year) may necessitate huge movement inland.
- Monsoonal floods increase, causing agricultural crop loss
- More than 75% of Sundarban, a pioneer mangrove forest of Bangladesh, would be lost; species like Sundri (*Heritera fomes*), the main economic species, would be replaced by Goran (*Cerops decandra*) and Gewa (*Excoecaria agallocha*). This would reduce the breeding grounds for many

estuarine fish, and the fish (protein) supply. Furthermore, the saline waters would move further up the delta reducing fresh water fish and having an adverse effect on cropland irrigation systems.

- As the habitat of wildlife would be destroyed, it would undoubtedly reduce the fauna, specially the Royal Bengal Tiger (*Panthera tigris*), an endangered species which may become extinct along with a number of plants and animals of Sundarban
- Storms and cyclones may occur again with a 10% increase in intensity, wind velocity would increase from 225 to 248 km per hour; storm surge rising from 7.1 metre to 8.6 metre.

The Asian Development Bank (ADB, 1994) presents the effects of climate change on the physiological indicators of plant performance as follows:

Table 5.5 Effects of hypothetical climate change on physiological indicators of plant performance (ADB, 1994).

Physiological indicators	C3 plants		C4 plants	
	Effects	Intensities	Effects	Intensities
Photosynthesis	+	****	+	**
Transpiration	-	***	-	**
Stomatal conductance	+	****	-	***
Respiration	-	***	-	**
Growth	+	***	?	?
Plant height	+	****		
Lodging	+	****		
Flowering	-	****	?	?
Anthesis	-	****	?	?
Maturity period	+	****	?	?
C-N ratio	+	****		
Yield	+	****	+	**

Here, +: increase; -: decrease; ****: very strong, ***: strong; **: mild;
*: insignificant; ?: unclear.

a) Flood in Bangladesh

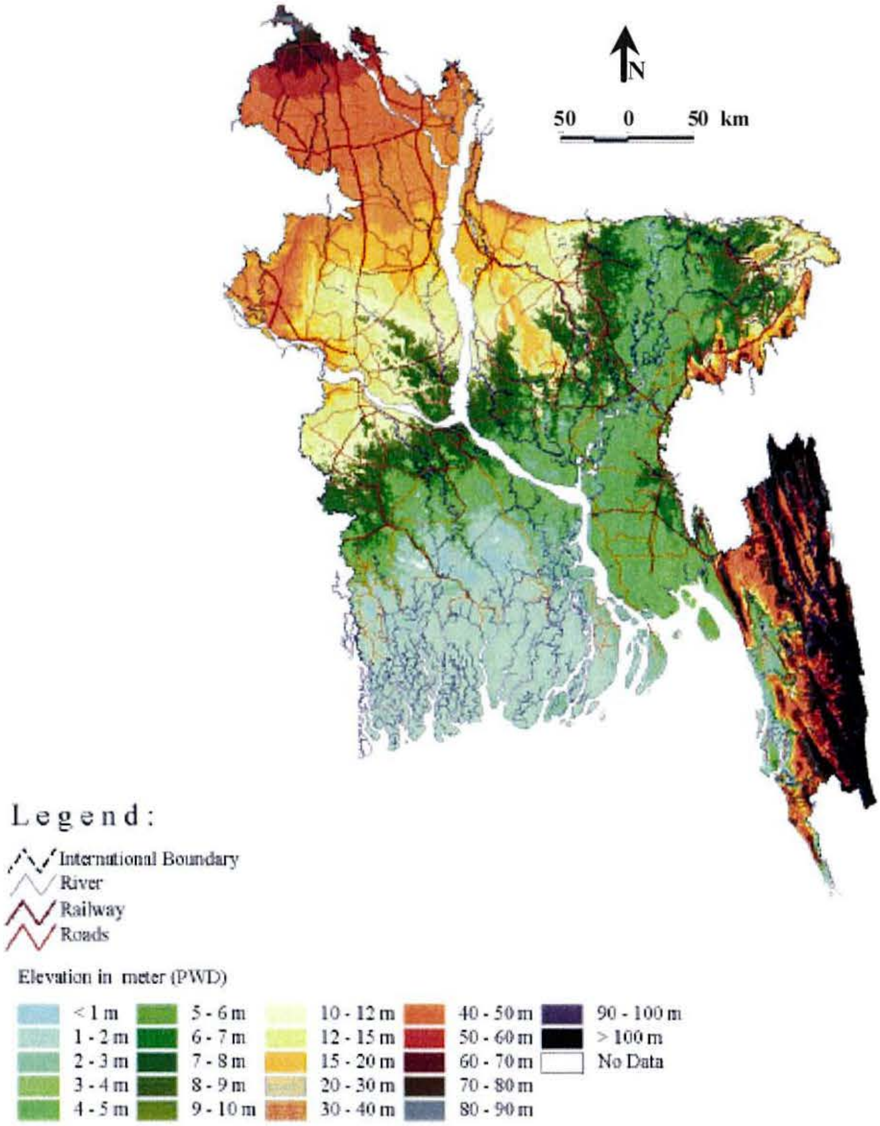
b) Flood in the United Kingdom

Photo 5.1 Shows the flood situations in Bangladesh and the United Kingdom (Source BBC, 2001); these types of flood situations will be more in future due to climate change; portraying that climate hazard is real, not discriminating whether a country is poor or rich, less developed or developed and tropical or temperate, in other words, it is global.

Application

Mulligan (1999) generated the climate change scenarios for the Snowdonia National Park. The CCSA model showed a way to use the Mulligan (1999) model for user-defined purposes. The hill forests of Chittagong and Cox's Bazar are situated by the side of the Bay of Bengal (as the Snowdonia National Park with the Irish sea). Thus the future climate change scenario map for regional level may be constructed using GIS, with the same procedure followed by Mulligan (1999) if the spatial data sets with climate attributes are available. The historical data sets preserved in weather stations may be very useful along with other spatial data sets to construct such scenarios for the future on a regional scale.

The digital elevation map for Bangladesh presented in Map 5.3, was generated by the Surface Water Modelling Centre (SWMC, 2000) which may be a very useful spatial dataset to generate climate change scenarios on a local basis incorporating temperature, precipitation and sea level changes for the future. Sea level rise is a very crucial issue for the future forests of the country. A present management (working) plan may include the future projected areas (particularly where the elevation is below 1 metre) which may be submerged by water (for harvesting) in the future, and preserve those areas that can cope with the climate change scenarios for the future (hill forests, where more vigilance and research to conserve the forests are needed). Newly emerged islands and chars in the Bay of Bengal may be another potential source for future afforestation programmes to stabilise and contribute to the horizontal extension of the country. However, it is wise to consider their potential contributions in the light of climate change.



Map 5.3 Digital elevation model of Bangladesh: a generalized topography for Bangladesh (adopted from SWMC, 2000).

CHAPTER SIX
GENERAL DISCUSSION AND CONCLUSIONS

6.1 General discussion

GIS was used to generate models for three topical issues (windthrow, carbon sequestration and climate change) in forest management. The discussion will firstly approach the contribution of spatial data sets underpinning the models, which were separately focused on in chapters 2, 3 and 4 and collectively presented in Figure 6.1. Secondly, it will consider the factors which influence the user-defined strategic forest management at a regional level. Thirdly, it will examine both the spatial data sets and strategic management factors influencing the performance and adoption of new data sets in their local planning and operational work, on a week-by-week basis. Finally, it will focus on the transferability of the theme of the study from the forest sector to other sectors and from one region to another part of the world.

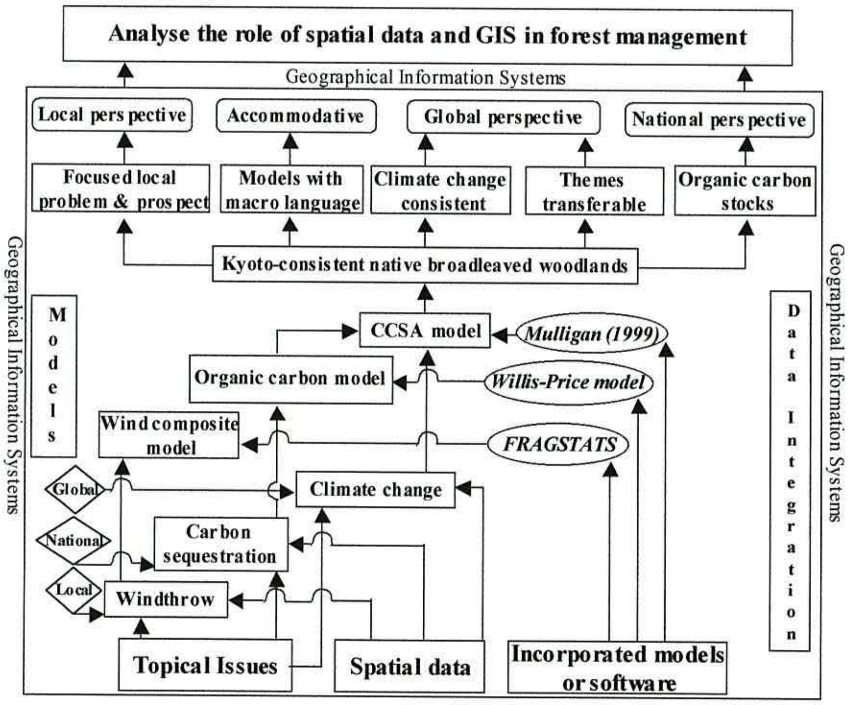


Figure 6.1 Illustrates the contribution of spatial data on topical issues of forest management to generate three models to focus on local problems and prospects with national and global perspectives.

6.1.1 Contributions of spatial data sets underpinning the models

This study focuses on the contributions of geographic information systems to provide the opportunity to assemble and analyse multiple layers of spatial data sets with tree, management and climate data sets. Spatial data sets such as soil, slope, altitude and exposure to wind were incorporated with the different models and software packages to generate a **w**ind **c**omposite **m**odel (WCM), an organic carbon model and a **c**limate **c**hange **s**cenarios **a**doption (CCSA) model in this study. Williams (1992) hypothesised that the spatial datasets would pass five levels to reach their final destination *i.e.* application at field level. The process of spatial data set integration and user-defined generated models satisfied the levels mentioned by Williams (1992) to reach the vision of the modeller. The approach of application of spatial data sets was used by Quine and Bell (1994) and Bell *et al.* (1995) for windthrow research in the UK, Wright and Quine (1993) to investigate storm damage in the UK, Chuvieco and Salas (1996) for forest fire hazard in Spain, Eastman *et al.* (1997) in environmental risk assessment, Bateman and Lovett (1998) to predict yield classes and Mulligan (1999) for climate change study in Wales, UK. The integration methodology of spatial data sets showed the need for clear vision of the modeller about the goal, as pointed out by Somers (1998).

Relevant management data sets such as tree and litter organic carbon stock in accordance to the yield class per hectare, are applied with the adjusted yield class generated by the spatial data sets of the study area. This arithmetical progression may operate through GIS only or a combination of spreadsheet analysis for easy understanding. In both cases, AREA function (measuring the area associated with each integer category of a map) with SCALAR function (performs arithmetic on the image by adding, subtracting, multiplying, dividing and exponentiating using a constant value) has a vital role to play in spatial data integration within GIS. The organic carbon model is an example of using both GIS and spreadsheet analysis to calculate the organic carbon stock for woodland. As management data are a product of growing science, any new development may be accommodated using macro routines.

Climatic datasets are also integrated with the spatial datasets to generate the **c**limate **c**hange **s**cenario **a**doption (CCSA) model. This model incorporates the climate change scenario maps of Mulligan (1999) with the spatial datasets of the study area to locate the potential native broadleaved woodland (PNBW) for the present and the future.

The ability to combine spatial data sets with different models (*Willis–Price*, tree carbon model and Mulligan (1999), potential NVC model) and software packages (FRAGSTATS) was made possible through this study. Figure 6.1 indicates that the DAMS (**D**etailed **A**spect **M**ethod of **S**coring) score map for the study area act as a spatial dataset for adjusted yield class determination in the organic carbon model. The maps of the scenarios and tree, litter and soil carbon stock of the organic carbon model were used in the CCSA model for the final estimation of organic carbon sequestration for present and future scenarios of Kyoto-consistent native broadleaved woodland.

It is revealed from these integration processes that IDRISI GIS has scope to integrate the spatial data sets and their derivatives to materialise a vision of a modeller successfully. This phenomenon was also agreed by Malczewski (1996) in large data set handling with the GIS approach of multi criteria decision-making in Canada, and Brown *et al.* (1998) in wet grassland management in the UK.

6.1.2 Factors describing strategic forest management at a regional level

The study considers windthrow as a local forest management problem, while creating new native broadleaved woodland is a prospect in the study area. Furthermore, organic carbon estimation procedure is needed to comply with the national scale, and CCSA model is needed because choosing the area for the native broadleaved woodland for the future is a global to local concern.

Windthrow

Windthrow is a hazard in the conifer plantations of the Snowdonia National Park. The Snowdonia National Park Authority (SNPA) is now looking for land under the control of the Forestry Commission to create new native broadleaved woodland. Both problem and prospect have been taken into consideration as practical examples for making a regional plan for the study area.

Gardiner and Quine (2000) pointed out the two main difficulties in calculating wind risk for a forest area: rooting strength and mapping wind flow in complex terrain. Rooting strength depends upon the soil and the tree physiology. Again, terrain wind flow depends upon the patches present in forest areas. Presently FORESTGALES, a computer package, is able to assess windthrow risk using DAMS (**D**etailed **A**spect **M**ethod of **S**coring) for UK plantations. DAMS was developed for the mainland of the UK and it needs to combine local factors to assess wind prone sites for the local area. Ruel (2000) agreed that local factors (soil and stand characteristics) make significant differences in windthrow from a local to a regional scale in Canada. The WCM combines the contributions of soil class, patch shape and leaf presence with DAMS in assessing windthrow risk. Quine (2001) agreed that patch shape and leaf presence are also potential factors for windthrow research.

The WCM is a multi-factor model incorporating patch shape, soil class and leaf presence in winter with DAMS data sets to indicate species suitability in the specified area. The approach of combining spatial datasets for management plans was also outlined by Williams (1992) to produce contra-indication classes for suitable grazing land in the Snowdonia National Park (SNP), Wales UK. Using FRAGSTATS for patch shape determination was also supported by Gkaraveli (1999), who used the same fragmentation analysis of forests of the SNP and combined the resultant maps with the spatial data sets.

The methodology of combining the factors is more important than the contribution provided because the contributions (%) of the considered factors can be replaced with any revision of the model. In other words, the proposed methodology demonstrated the integration of spatial datasets and techniques from different sources, with different formats, structures or projections within the GIS, which may be a useful tool when combining different responsible factors with DAMS for wind risk assessment to choose alternative landuse. This approach is agreed by Payn *et al.* (1999) to use spatial analysis to monitor changes in forest productivity in New Zealand.

Disturbances of *Picea* plantations may lead the forest to be diversified with the broadleaves in boreal forests (Syrjanen *et al.*, 1994 quoted in Quine, 1999). Therefore, considering the "*too windy*" situation according to the WCM, the selection of land in the study area, for native broadleaved woodland as scrubby forest, may be justified.

Carbon sequestration

Carbon emission in the UK is very crucial because the government had a target to reduce the emission by 20% from the level of 1990 (DETR, 2000). On the other hand, forests with their vegetation and soil resources are effective sinks of carbon when they are conserved and not disturbed, otherwise they may be a source of carbon.

Spatial data sets were used to identify the adjusted yield classes of the plantations in the study area and then the adjusted yield classes (AYC) were used to estimate tree and litter organic carbon stocks for the plantations. Moreover, the spatial data sets about soil types were also applied to estimate the soil organic carbon stock up to one-metre soil depth. In both cases, the relevant data were taken from different sources and applied with the GIS-spreadsheet model to estimate the total organic carbon for the conifer plantations in the study area. The study also showed the scenarios portraying the sites which would lock as much organic carbon as the conifer plantations if the sites were replaced by native broadleaf species oak. It also compared yield classes of broadleaf and conifer on the basis of total carbon sequestration. The results of the study revealed that yield class 02, 04 and 06 of oak enabled the fixing of as much organic carbon up to AYC 06 (scenario 1: 70 hectares), AYC 12 (scenario 2 (AYC 08 to 12): 6029 hectares), AYC 16 (scenario 3 (AYC 14 to 16): 4888 hectares) of conifer plantations respectively.

This estimation procedure may help the concerned authority to draw a sketch of a National Grid for Carbon (NGC) for the future. A forester may be able to tell how much organic carbon the forest possesses now, then forecast how much will be removed and replaced in the near future. The proposed National Grid for Carbon (NGC) may then be a source of information for the policy maker.

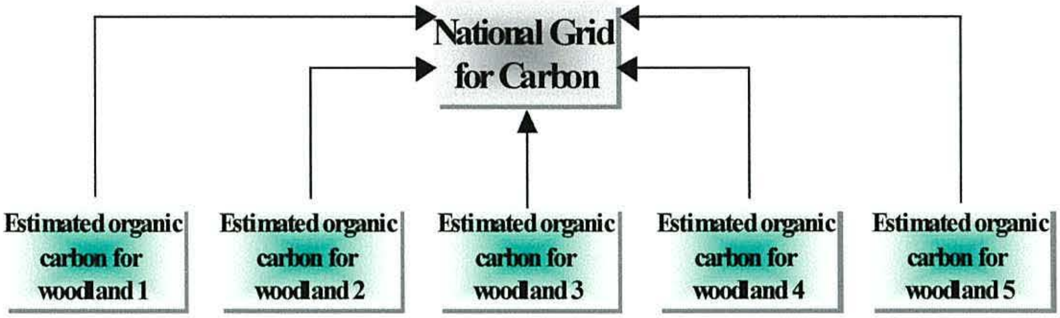


Figure 6.2 Hypothetical schematic flow of a part of the National Grid for Carbon (NGC) for the forestry sector.

Improved estimation of terrestrial organic carbon sequestration is an important global issue, particularly as, to date, little attention has been paid to estimating soil organic carbon sequestration and loss (Cannell *et al.*, 1999). However, it seems that organic carbon estimation on a micro level is becoming a priority for research, indicating that better results may be produced in the future. This piece of research adopted a simple and novel methodology to estimate the organic carbon stocks from the various sources and then applied the information (data) within the GIS-spreadsheet organic carbon model. Use of spatial datasets in the estimation of organic carbon is also supported by Bateman and Lovett (2000) in Wales, UK. The results of the estimated soil organic carbon for the study area depicted that the soil is the highest contributor (73%) of organic carbon stock for the study area because large tracts of forest are on the organic carbon rich soils. However, Thornley and Cannell (2001) also proposed to consider the buried organic carbon in total organic carbon estimation.

The methodology for the estimation of organic carbon may provide a basis for the forest manager to replace conifer with broadleaf species. Furthermore, as the yield class determination process incorporates DAMS scores, it may visualise three general things: it mimics windthrow risk, locates the sites which may produce more organic carbon and is also expressed in the stand production system (yield class).

Climate change

A forest is an open resource to the atmosphere, spatial and temporal factors are working on its management. A forest manager has to be aware of these factors because her/his decision is very crucial, since long-term investments are needed to carry out forestry activities. Therefore, climate change scenarios are important for any future forest management programme.

The lands were located with the three additive scenarios (section: 3.4.5) in organic carbon model which enabled to produce more organic carbon if the conifer plantations were replaced by oak. However, climate change in future was not considered to locate the areas of these three scenarios. The CCSA model considered the high and low climate change scenarios of the UKCIP 1998, by using the maps of PNBW for the future (2080) with the high and low climate change scenarios of Mulligan (1999) for the Snowdonia National Park. When the areas of the three scenarios of the organic carbon model were applied with the CCSA model, the potentially suitable and climatically adaptable areas for native broadleaved woodland (Figure 6.3) for future (2080) were predicted and located in maps. The located site areas of PNBW for future (2080) with CCSA model were varied from the organic carbon model. This may due to increase of temperature in future which may facilitate some plant communities to migrate to the higher altitude (cooler) but mainly small land area available in higher altitude in the study area. The modelled PNBW for future (2080) may be able to fix as much organic carbon as the conifer if the broadleaf species oak replaced the sites (71,410 tonnes and 81,366 tonnes more organic carbon with high and low climate change scenarios respectively than conifer). Hence it is a step forward to meeting the demand of increasing the rate of the UK organic carbon sequestration. These sites may be climatically suitable for future and are termed as Kyoto-consistent forests. However, Kyoto consistent forests are forests which are managed by human activities as a result of land use change, and are able to lock carbon so as to meet the Kyoto commitments. Figure 6.3 illustrates three CCSA scenarios, considering high and low climate change in 2080, the areas available for the forest manager to consider for future Kyoto-consistent native broadleaved woodland in the study area.

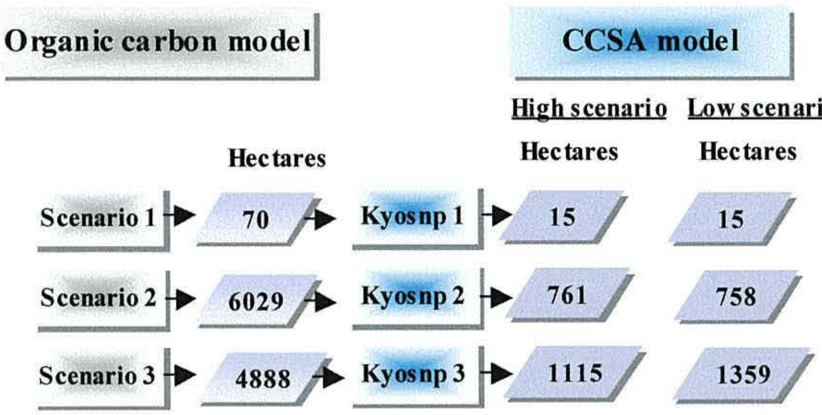


Figure 6.3 Showing the areas calculated with the organic carbon and CCSA model for native broadleaved woodland for the future. Areas under the CCSA model may be the Kyoto consistent forests of the future.

The Snowdonia National Park Authority (SNPA) may present the scenarios to the Forestry Commission in order to show the long-term differences between organic carbon sequestration by the existing plantations and that of the future native broadleaved woodland, as they are looking for lands to create new native broadleaved woodland (SNPA, 1995).

6.1.3 Adoption of new data sets in local planning and operational work

The forest resource management system is now an integrated management with different disciplines such as agriculture, hydrology, climatology, wild life *etc.* using different sources of data with different formats and structures. When a model is generated with these data sets, sometimes modification is needed for application in local and operational work on a week-by-week basis. Suppose some trees of a forest were harvested what will be the consequences of this gap for future native woodland creation? Furthermore, if a policy maker changes her/his decision about models then what will be the fate of the models? Considering these types of issues, models are generated with macro languages of IDRISI GIS which can cope with any change by updating the spatial datasets and running the model within GIS for the day-to-day scenarios. Although the results of the models presented in this study may not be a hundred percent predictive, because of the consistency of the input data sets, it has the potential to generate the best estimates with accurate data sets. This accommodative ability of models enables the manager to have an easy understanding and shows the scenario to the policy maker within short notice. Malczewski (1995) used macro language for drawing hypothetical decision-making within a GIS environment in Canada. Mulligan (1999) also used macro languages in his climate model for the SNP of Wales, UK, facilitating the adoption of the climate scenarios to generate the CCSA model.

6.1.4 Transferability of the theme of the study from the forest sector to other sectors, and from one region to another parts of the world.

The theme of the study, *i.e.* using GIS in week-by-week activities of forest management regional planning, may be transferable with the generic version of the models, particularly with macro language. Although the models discussed in this study are case studies for the Snowdonia National Park in Wales, UK, the methodology developed to generate models may be transferable to any temperate or tropical regions to perform resource management systems such as agriculture, rural resources, housing development and flood area assessment.

Chapter 5 discussed the possibility of transferring the knowledge of modelling to different aspects of forest resource management of Bangladesh by creating similar spatial datasets for the country and putting them into the macro based modelling system to obtain the management decision. The 'tatter-flag' system to calculate site windiness is a cheap and transferable technology for any developing country, and a step forward to estimate windiness. This approach is also agreed by Dhubhain (1999) who recommend its application in Irish forestry management.

6.2 Conclusions

This study does not produce a comprehensive forest management system concerning all the issues which may contribute to forest management. It does, however, suggest that spatial data sets and GIS may contribute significantly in forest management, particularly when three topical issues are considered: windthrow, carbon sequestration and climate change. Furthermore, GIS-based forest management may accommodate week-by-week activities into the database in order to derive the management decision.

GIS enables one to combine spatial data sets with different models and software for practical use in forest management. Combining FRAGSTATS in the WCM, the *Willis–Price* tree carbon model in the organic carbon model, and Mulligan's (1999) maps about PNBW considering high and low climate change scenarios of UKCIP 1998 in the CCSA model, are the case studies discussed in this study.

Three process models were generated regarding windthrow, carbon sequestration and climate change, considering local problems and the prospects of forest management, particularly for the conifer plantations of the study area (the Snowdonia National Park).

- The WCM offered methodology of a simple approach to integrate spatial datasets and techniques using GIS to obtain the four scenarios of WCM maps over a forest area. Combining contributions of soil class, patch shape and leaf presence in winter with the DAMS (detailed aspects of method of scoring) score generated four scenarios of WCM using the GIS framework.

  Implementation: The WCM may be used for educational purposes, to demonstrate how GIS technology may be applied to integrate spatial data sets for practical purposes from a national scale to a local one and to narrate a PC-based forest management system.

- The organic carbon model outlined the methodology of integrating spatial data sets to generate adjusted yield classes. It also estimates organic carbon contents regarding adjusted yield classes of the forest area. Adjusted yield classes (AYC) are created by combining the effects of spatial data sets of land use, altitude, slope, aspect and exposure to wind (DAMS) using GIS with the yield classes prescribed by Pyatt (1977) with local expert opinion (Stevens, 2001). Tree, litter and soil organic carbon stocks concerning adjusted yield classes are estimated using GIS–spreadsheet analysis.

  Implementation: The methodology for generating the organic carbon model may be useful to estimate carbon sequestration from small woody tracts to large woodlands. This model may be useful to set up a grid for carbon in a forestry sector on a national scale.

- The CCSA model generated the methodology of integrating spatial data sets and climatic variables, such as temperature and precipitation, with future climate change scenarios: UKCIP 1998, using GIS. The scenarios developed in the organic carbon model are applied with the high and low climate scenarios of UKCIP 1998 with the maps of Mulligan (1999) to predict future native broadleaved woodland for the study area.

  Implementation: The CCSA model may be useful for implementing a new afforestation or harvesting programme to predict the future impacts regarding climate change.

All the models may act individually and also collectively for integrated forest management within the GIS framework. The models incorporate the windthrow problem of the study area, whilst also looking at the land to create new native broadleaved woodland with an indication of how much organic carbon may be sequestered. Finally, the potential land for native broadleaved woodland, in the conifer plantations of the study area with the CCSA model, showed three scenarios with each climate change scenario for 2080.

All the models were run using the macro language of IDRISI GIS, which facilitates upgrading, adding or removing spatial datasets which may assist the manager with new policy decisions. It is also evident that the principles used for generating the methodologies for models are transferable to other disciplines of resource management, and also to other countries.

6.3 Recommendations for future research

There have been few documented studies on the application of spatial data sets in forest management, particularly macro-based GIS modelling systems for forests. The following therefore focuses on the most important areas for further research in view of the findings of the present study.

6.3.1 General and for the UK

Patch shape and leaf presence with DAMS are likely to present a significant role in windthrow studies. The present study did not focus on the exact contributions of these two factors with the specific terrain. The efficiency of the modelling of windthrow may be more precise if the contributions of factors along with patch orientation are measured with the application of ForestGALES considering a field-based study.

Soil organic carbon in particular is a potential field for thorough study. Considering the heterogeneous behaviour of soil, organic carbon contents of soil layers are different from one forest to another. This study did not investigate beyond one-metre depth of soil profile for carbon content. There are, to date, no data regarding the organic carbon content of different soil classes with a reasonable depth of soil profile with different land uses (such as conifer and broadleaf), for the Snowdonia National Park; this may be a promising sector for further study. The study did not investigate any economic valuation of sequestered organic carbon, which is also a potential field of research to make a valuation of tree, litter, and soil organic carbon.

The present study only considered climate change scenarios developed with temperature and precipitation data sets for upland forest management. There is ample scope to include other climate variables such as wind, sun-light, relative humidity *etc.* for improved prediction in forest management using GIS, particularly macro based.

6.3.2 Bangladesh

The present study has not investigated any research regarding the forest management of Bangladesh. GIS modelling is a new aspect of technology for forest management in Bangladesh. Research is needed to accumulate the basic information from different spatial factors and then use them in modelling and field-based studies using GIS in Bangladesh.

However, all the issues mentioned in chapter five (Themes Transferable to Bangladesh) along with macro based GIS and GIS modelling in general, have scope for application in Bangladesh. This is particularly appropriate in site index preparations for species, harvesting, afforestation and reforestation programme and to mitigate forest based socio-economic problems, specially, the social and agro-forestry programmes in the forest management of Bangladesh which were not covered in this study. GIS can contribute a lot in flora and fauna management in mangrove ecosystems predominantly in the *Sundarban* mangrove forests, especially in the monitoring of endangered species.

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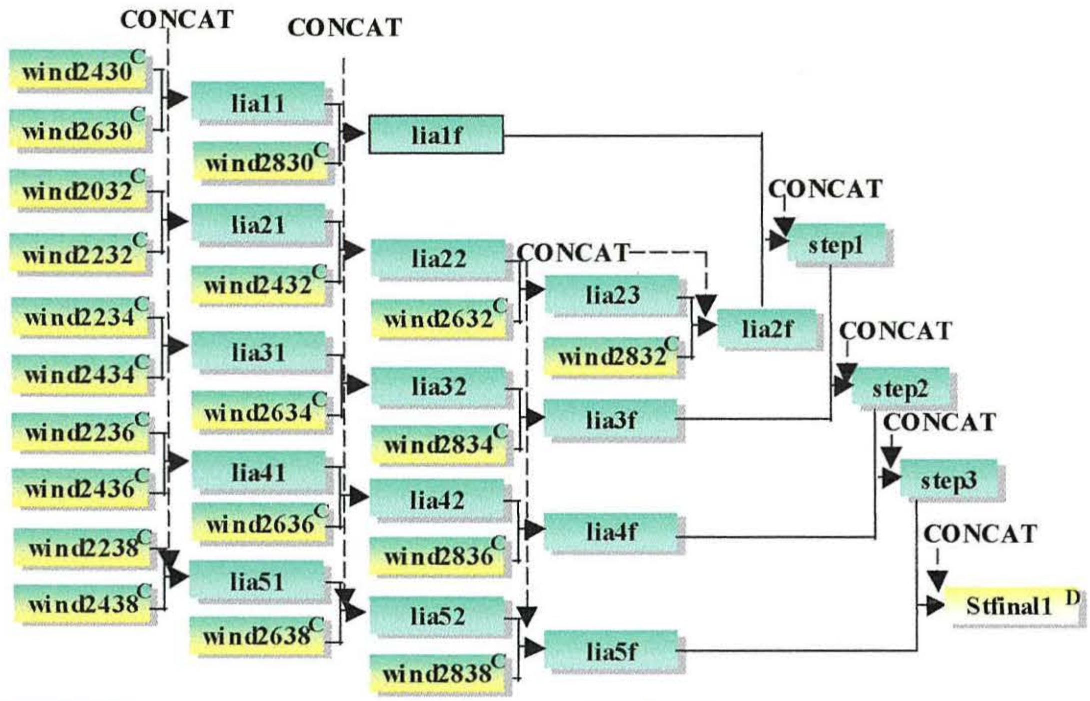
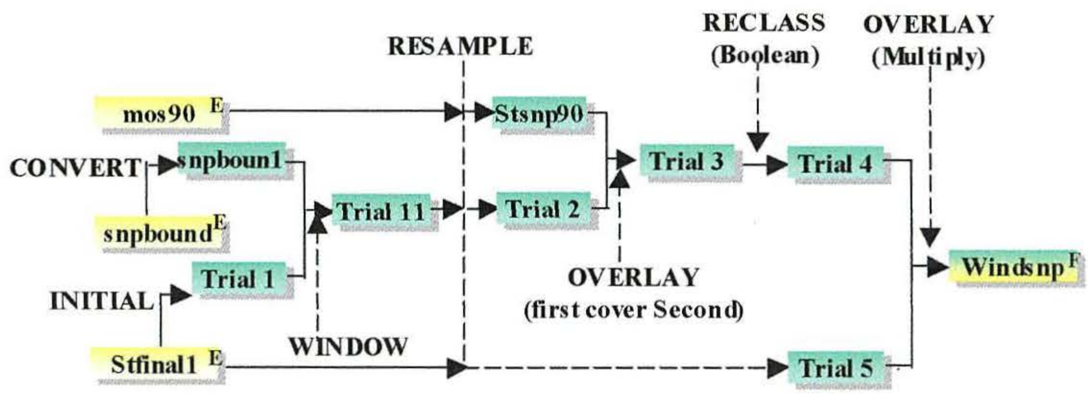
LIST OF APPENDICES

Appendix 2.1. Flow figures of map generation using GIS in windthrow study.



C = supplied tile of DAMS data. D = Concatenated map of DAMS data

Figure 1 A. GIS procedures followed in the assembly of supplied DAMS data sets.



E = Input maps F = Output DAMS map for study area

Figure 1B. The flow diagram illustrates the GIS procedure for creating DAMS data set map for the study area.

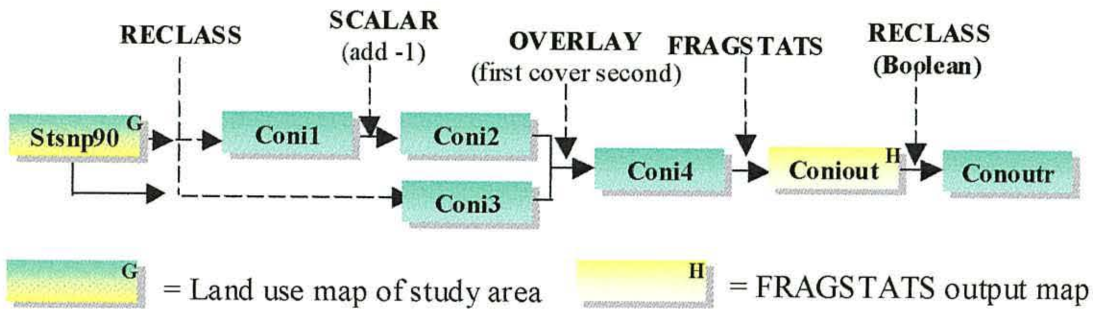


Figure 1C. GIS procedures for creating map with patch matrices of conifer plantations in study area.

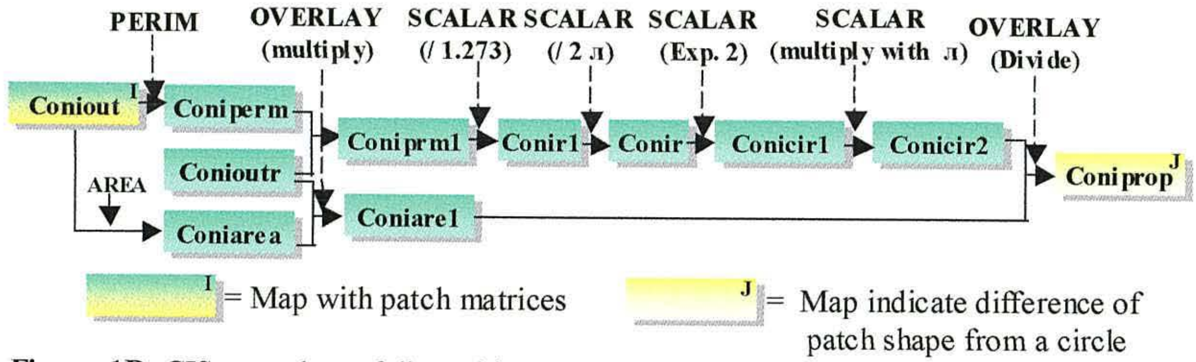


Figure 1D. GIS procedures followed in creating a map to indicate the ratio between the area covered by patch and the area covered with a circle of same perimeter.

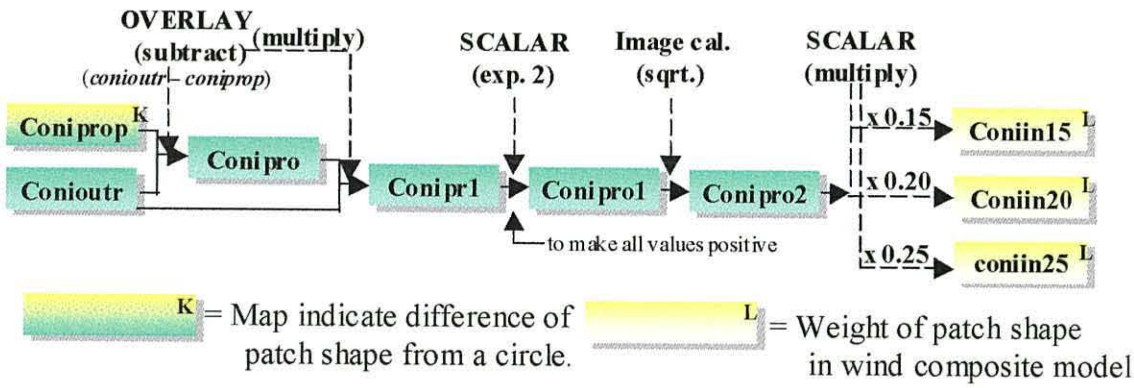


Figure 1E. GIS procedures for contribution of patch shape with 15%, 20% and 25% contributions

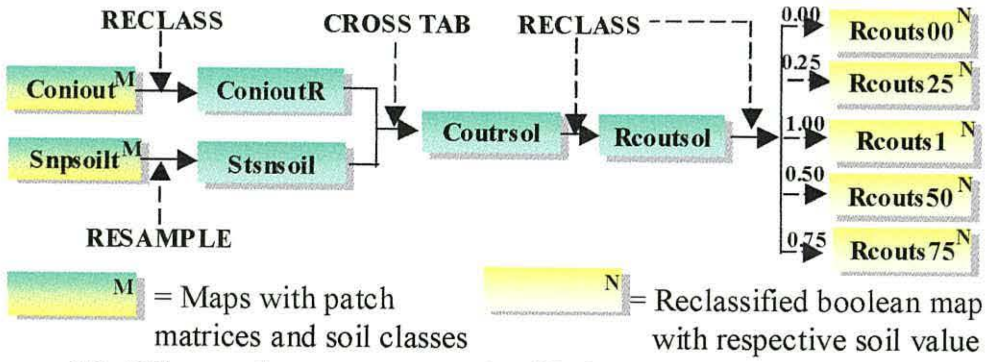


Figure 1F. GIS procedures to create reclassified maps with the score of the soil classes from appendix 2.5

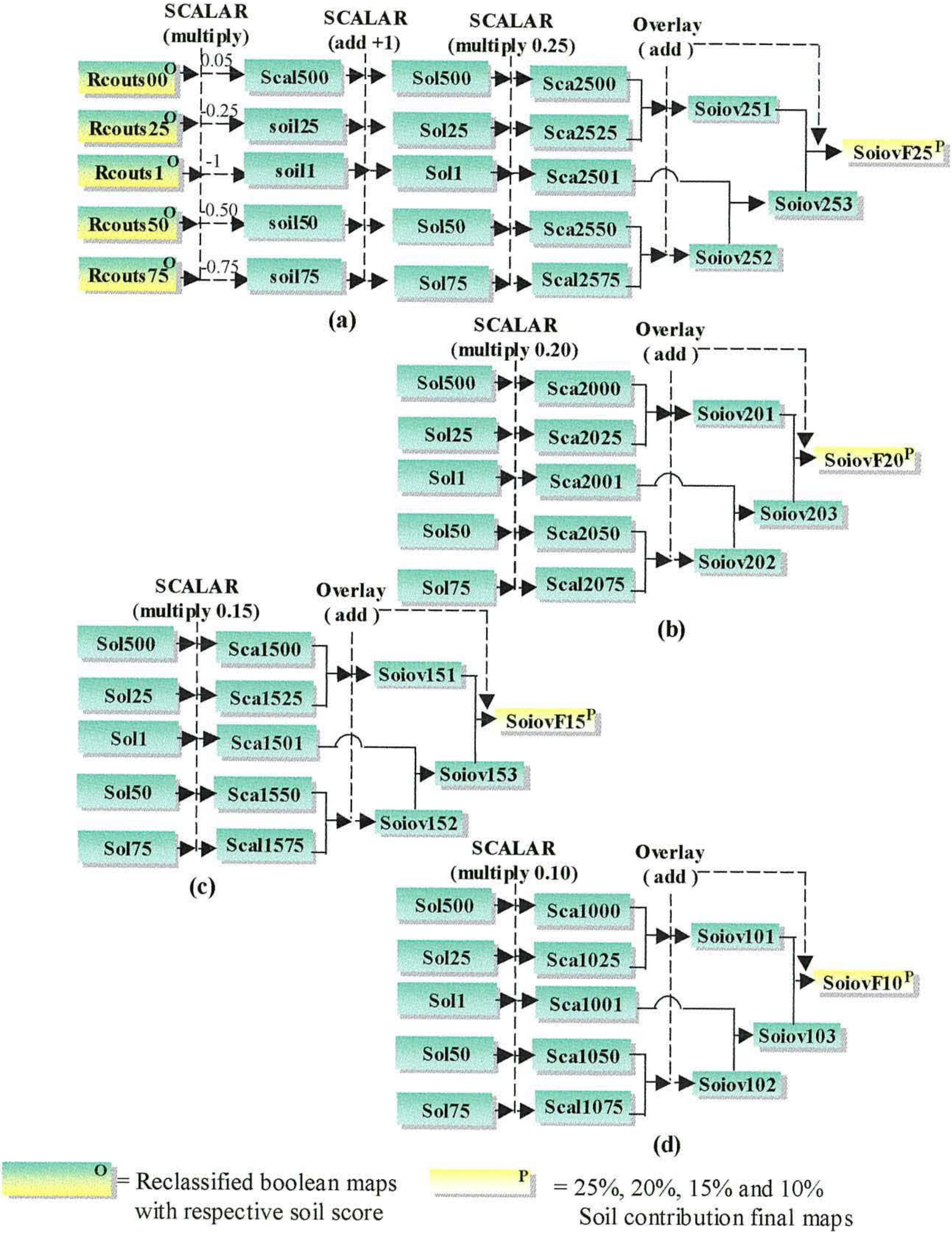
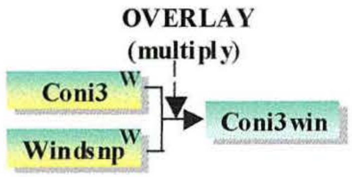
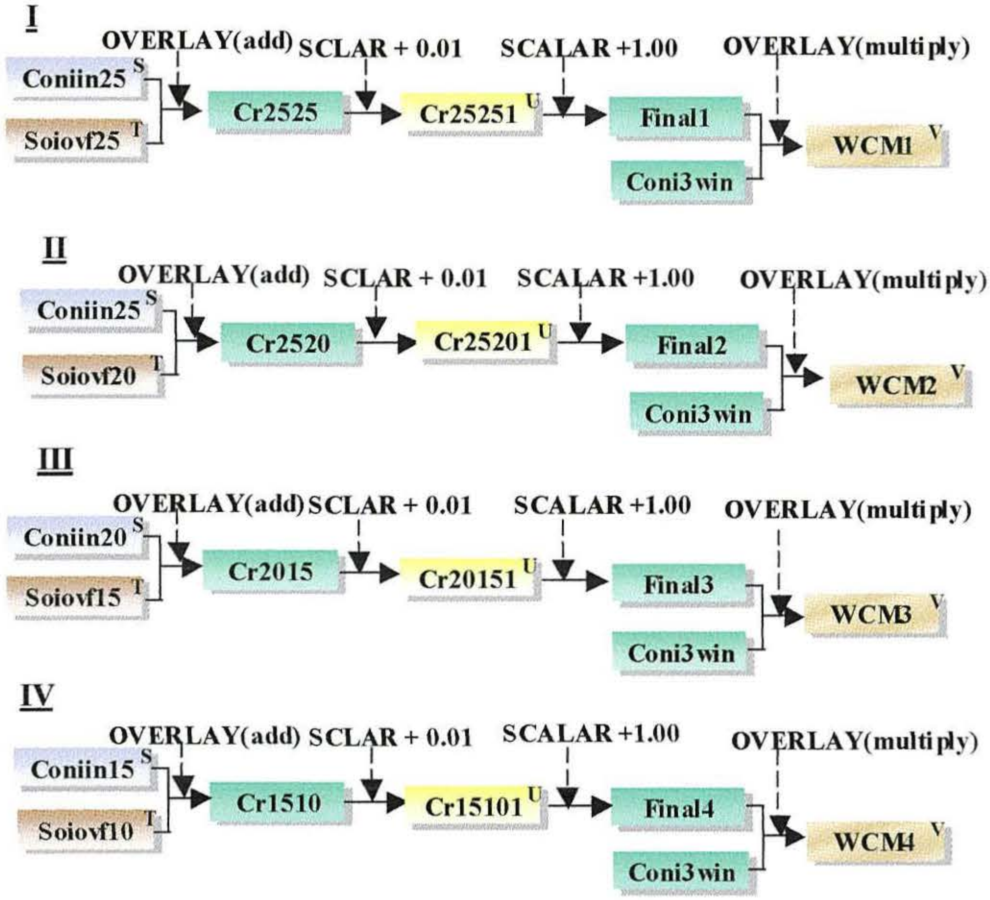


Figure 1G. a) 25% b) 20% c) 15% and d) 10% contributions of soil classes



W = Maps with conifer and the DAMS score in the study area.

Figure 1H. Map with DAMS score with the conifer plantations of the study area.



S = Patch shape T = Soil class U = includes leaf presence V = WCM

Figure 1I. GIS procedures for creating maps(I to IV) of four combination scenario of WCM

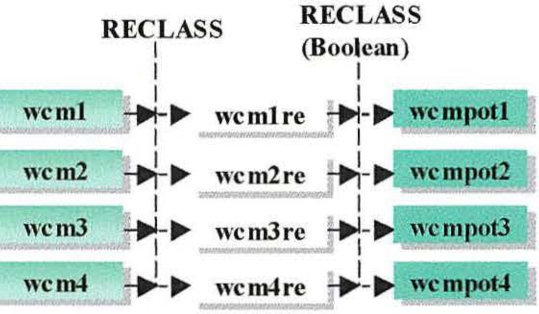


Figure 1J. GIS procedures for creating maps according to the target native woodland of SNPA with four scenarios of WCM.

<u>Appendix 2.2</u>: Macro statements for simulating four combination scenarios of Wind Composite Model (WCM) in IDRISI format

Following IDRISI GIS functions were applied to simulate the new WCM model and to predict the impacts of the models in the study area. The generic format (Malczewski, 1996) of a statement for operations related to a single map layer is written as follows: COMMAND Input MAP_ID FOR Output MAP_ID, and for operations related to two or more map layers:

COMMAND (Input Map_ID operation Input Map_ID) FOR Output MAP_ID.

CONCAT : It allows the pasting together of images to form a larger one.

Macro command line:
1 : x (to indicate that batch mode is being used)
2 : main reference image (the name of the main reference image)
3 : number of paste images (number of images to be pasted to main image)
4 : output image name (the new image file to be created)
5 : concatenation procedure (1 = paste images opaquely cover the main ref image / 2 = main ref image transparently covers paste image)
For each paste image enter parameters 6 through 9
6 : paste image name (name of the paste image)
7 : reference corner to use (1=upper-left / 2 =lower-left / 3 = upper-right / 4= lower-right)
8 : column position (column position for placement of this corner)
9 : row position (row position for placement of this corner)

CONVERT: It converts files between all possible combinations of data and file types supported for image and vector files.

Macro command line:
1 : x (to indicate that batch mode is being used)
2 : input file name (the file to be converted)
3 : output file name (the result [may be the same as the input image])
4 : graphic type ("i" = image / "v" = vector)
If graphic type is image, then:
5 : output data type (1= integer / 2 = real / 3 = byte)
6 : output file type (1= ASCII / 2 = binary / 3= packed binary)
7 : integer conversion type (1= truncation / 2= rounding [optional - default=2])
If graphic type is vector, then:
5. output data type (1= integer / 2= real)
6. output file type (1= ASCII / 2 = binary)
7. integer conversion type (1= truncation / 2= rounding [optional - default=2])

RESAMPLE : It registers the data in one grid system to a different grid system covering the same area.

Macro command line:

1 : x (to indicate that batch mode is being used)
2 : file type (i = image / v = vector)
3 : input file name (existing file to be resampled)
4 : output file name (the new file to be created)
5: correspondence file name (control point correspondence file name; ".cor" extension is assumed)
6 : new reference system (name of the final reference system)
7 : new reference units (m / deg / ft / km / mi / rad) (enter exactly as shown, i.e., m, not meters)
8 : new unit distance (unit distance of the final reference system [1.0])
9 : background value (value to be used for background areas [e.g., 0]; enter "0" for a vector file)
10: minimum X (min x value of the output file)
11: maximum X (max x value of the output file)
12: minimum Y (min y value of the output file)
13: maximum Y (max y value of the output file)
14: number of columns (number of columns that will span this region; enter "0" for a vector file)
15: number of rows (number of rows that will span this region; enter "0" for a vector file)
16: mapping function (1= linear / 2 = quadratic / 3 = cubic)
If file type in # 2 is i (image), then
17: resampling type (1 = nearest neighbor / 2 = bilinear)

INITIAL: It creates new images with a constant value.

Macro command line:

1 : x (to indicate that batch mode is being used)
2 : output image name (the new image file to be created)
3 : output data type (1= integer / 2 = real / 3 = byte)
4 : output file type (1= binary / 2 = ASCII)
5 : initial value (the value each cell will have, e.g., 0)
6 : how parameters defined (1 = copy from existing image / 2 = define individually)
7 : defining image file (name of image file to copy parameters from)
8 : value units (the units of the data values in the image)

OVERLAY: Overlay produces a new image from the data on two input images. The module can add, subtract, multiply, ratio, normalised ratio, exponentiate, cover, minimise and maximise the data set of two input images.

Macro command line:
1 : x (to indicate that batch mode is being used)
2 : operation number (overlay operation – please see options below)
3 : first input image (the first image in the overlay)
4 : second input image (the second image in the overlay)
5 : output file name (the new image file to be created)
Operation options are: 1 : Add, 2 : Subtract, 3 : Multiply, 4 : Ratio (first/second), 5 : Normalized Ratio ((first-second)/(first+second)), 6 : Exponentiate (first to the power of the second), 7 : Cover (first covers second unless zero), 8 : Minimum, 9 : Maximum.

RECLASS : It classifies or reclassifies the data stored in images or attribute values files into new integer categories.

Macro command line:
1 : x (to indicate that batch mode is being used)
2 : file type ("i"=image / "a"=values file)
3 : input file name (the file to be reclassified)
4 : output file name (the new file to be created)
5 : classification type (1= equal interval/ 2 = user defined / 3 = file mode)
If classification type is 1, then
6 : minimum (specify "min" to use actual min or enter new min)
7 : maximum (specify "max" to use actual max or enter new max)
8 : number of classes (specify integer number or real num. class width)
If classification type is 2, then ... (6-8 may be repeated)
6 : new value (assign a new integer class value of ...)
7 : old start value (for the old values ranging from ...)
8 : old end value (to those just less than ...)
n : -9999 (end of sequence code: same as "q" in manual mode)
If classification type is 3, then ...
6 : ".rcl" text file name (text file name, without the extension.

PERIM : PERIM measures the perimeter of each category in a grouped integer image.

Macro command line:

1 : x (to indicate that batch mode is being used)
2 : input file name (image to use for perimeter calculation)
3 : output format (1=image / 2=values file)
4 : unit type (calculate perimeter in 1= sides / 2 = meters / 3 = feet / 4 = kilometers / 5 = miles)
5 : output file name (name of resulting file)

SCALAR: It does scalar arithmetic on images by adding, subtracting, multiplying, dividing, or exponentiating the pixels in the input images by a constant value.

Macro command line:
1 : x (to indicate that batch mode is being used)
2 : input image name (the file to be acted upon)
3 : output image (the new image to be created)
4 : operation number (the operation to be performed)
5 : the scalar value (the value to be used in that operation)
Operation options are: 1 : Add, 2 : Subtract, 3 : Multiply, 4 : Divide, 5 : Exponentiate.

AREA: It measures the areas associated with each integer category on an integer image.

Macro command line:

1 : x (to indicate that batch mode is being used)
2 : input file name (image to use for area calculation)
3 : output format (1=image / 2=values file)
4 : unit type (unit of measurement for output calculation; see options below)
5 : output file name (name for resulting file)
Unit types are: 1 : cells, 2 : hectares, 3 : acres, 4 : sq. meters, 5 : sq. feet, 6 : sq. km,
7 : sq. miles.

CROSSTAB: It performs two functions. The first is image cross tabulations in which the categories of one image are compared with those of a second image and a tabulation is kept of the number of cells in each combination.

Macro command line:

1 : x (to indicate that batch mode is being used)
2 : first image name (first image in the cross-tabulation)
3 : second image name (second image in the cross-tabulation)
4 : output type (see choices below)
For output types 1-3
5 : output image name (resulting cross-classification image name; if ouput type is 2, enter "none")
Output types are: 1 : cross-classification image, 2 : full cross-tabulation table, 3 : both cross-classification and tabulation, 4 : image similarity/association data only.

6 : print KIA output? (Y/N - print Kappa Index of Aggreement values?)

Macro statements

*(Basic input images are Supplied image for landuse: **mos90**, soil: **SNPsoilt**, DAMS: after concatenation **Stfinal1** (wind 2032 to wind2838) and patch shape FRAGSTAT image: **coniout**.).*

2.2.1. Concatenation

```
concat   x wind2430 1  lia11    1 wind2630 1  401 0
concat   x    lia11 1  lia1f    1 wind2830 1  802 0
concat   x wind2032 1  lia21    1 wind2232 1  401 0
concat   x    lia21 1  lia22    1 wind2432 1  802 0
concat   x    lia22 1  lia23    1 wind2632 1 1203 0
concat   x    lia23 1  lia2f    1 wind2832 1 1604 0
concat   x wind2234 1  lia31    1 wind2434 1  401 0
concat   x    lia31 1  lia32    1 wind2634 1  802 0
concat   x    lia32 1  lia3f    1 wind2834 1 1203 0
concat   x wind2236 1  lia41    1 wind2436 1  401 0
concat   x    lia41 1  lia42    1 wind2636 1  802 0
concat   x    lia42 1  lia4f    1 wind2836 1 1203 0
concat   x wind2238 1  lia51    1 wind2438 1  401 0
concat   x    lia51 1  lia52    1 wind2638 1  802 0
concat   x    lia52 1  lia5f    1 wind2838 1 1203 0
concat   x    lia1f 1  step1    1     lia2f  4 1203 0
concat   x    step1 1  step2    1     lia3f  4 2005 0
concat   x    step2 1  step3    1     lia4f  4 2006 0
concat   x    step3 1  stfinal1 1     lia5f  4 2007 0
```

2.2.2. Input and DAMS data map for study area

```
convert  x mos90 mos90co i  3 2 2
resample x i  mos90co  stsnp90  alamin plane m  1 0 245575 300325 299975 379425 1095 1589 1 1
resample x i  stfinal1  trial5  alamin plane m  1 0 245575 300325 299975 379425 1095 1589 1 1
initial x trial1  2 1 0  1 stfinal1 scores
convert  x snpbound  snpboun1 v   2  2  2
lineras  x snpboun1  trial1
window x trial1   trial11   1 913 412 2007 2000
resample x i  trial11  trial2 alamin  plane m  1 0 245575 300325 299975 379425 1095 1589 1 1
overlay  x  7 stsnp90  trial2 trial3
reclass  x i  trial3   trial4   2    0  0 1 1    1  9999  -9999
overlay  x  3 trial4   trial5 windsnp
```

2.2.3. FRAGSTAT image

```
reclass  x   i  stsnp90  coni1   2   1 0  1 0  1 9999 -9999
scalar   x  coni1 coni2     1   -1
reclass  x   i  stsnp90  coni3   2   0 0 16 1 16   17  0   17 9999 -9999
overlay  x   7  coni2    coni3  coni4
```

2.2.4. Patch shape contribution

perim	x	coniout	1	2	coniperm
overlay	x	3	coniperm	conioutr	coniprm1
scalar	x	coniprm1	conir1	4	1.273
scalar	x	conir1	conir	4	6.282
scalar	x	conir	conicir1	5	2
scalar	x	conicir1	conicir2	3	3.142
area	x	coniout	1	4	coniarea
overlay	x	3	coniarea	conioutr	coniare1
overlay	x	4	coniare1	conicir2	coniprop
overlay	x	2	conioutr	coniprop	conipro
overlay	x	3	conipro	conioutr	conipr1
scalar	x	conipr1	conipro1	5	2

conipro2 came from the square root of conipro1 using Image calculator.

scalar	x	conipro2	coniin15	3	0.15
scalar	x	conipro2	coniin20	3	0.2
scalar	x	conipro2	coniin25	3	0.25

2.2.5. Soil class contribution

reclass x i coniout conioutr 3 conioutr
resample x i snpsoilt stsnsoil alamin plane m 1 0 245575 300325 299975 379425 1095 1589 1 1
crosstab x conioutr stsnsoil 1 coutrsol n
reclass x i coutrsol rcoutsol 3 rcoutrso
reclass x i rcoutsol rcouts00 3 rcouts00
reclass x i rcoutsol rcouts25 3 rcouts25
reclass x i rcoutsol rcouts1 3 rcouts1
reclass x i rcoutsol rcouts50 3 rcouts50
reclass x i rcoutsol rcouts75 3 rcouts75
scalar x rcouts00 Scal500 3 -0.00
scalar x rcouts25 soil25 3 -0.25
scalar x rcouts1 soil1 3 -1.00
scalar x rcouts50 soil50 3 -0.50
scalar x rcouts75 soil75 3 -0.75
scalar x Scal500 Sol500 1 1.00
scalar x soil25 sol25 1 1.00
scalar x soil1 sol01 1 1.00
scalar x soil50 sol50 1 1.00
scalar x soil75 sol75 1 1.00

2.2.5.1. Soil class with 25% contribution

scalar x Sol500 sca2500 3 0.25
scalar x Sol25 sca2525 3 0.25
scalar x Sol1 sca2501 3 0.25
scalar x Sol50 sca2550 3 0.25
scalar x Sol75 sca2575 3 0.25
overlay x 1 sca2500 sca2525 soiov251
overlay x 1 sca2550 sca2575 soiov252
overlay x 1 sca2501 soiov252 soiov253
overlay x 1 soiov251 soiov253 soiovf25

2.2.5.2. Soil class with 20% contribution

```
scalar x Sol500   sca2000 3  0.2
scalar x Sol25    sca2025 3  0.2
scalar x Sol1     sca2001 3  0.2
scalar x Sol50    sca2050 3  0.2
scalar x Sol75    sca2075 3  0.2
overlay x  1 sca2000  sca2025  soiov201
overlay x  1 sca2050  sca2075  soiov202
overlay x  1 sca2001  soiov202 soiov203
overlay x  1 soiov201 soiov203 soiovf20
```

2.2.5.3. Soil class with 15% contribution

```
scalar x Sol500   sca1500 3  0.15
scalar x Sol25    sca1525 3  0.15
scalar x Sol1     sca1501 3  0.15
scalar x Sol50    sca1550 3  0.15
scalar x Sol75    sca1575 3  0.15
overlay x  1 sca1500  sca1525  soiov151
overlay x  1 sca1550  sca1575  soiov152
overlay x  1 sca1501  soiov152 soiov153
overlay x  1 soiov151 soiov153 soiovf15
```

2.2.5.3. Soil class with 10% contribution

```
scalar x Sol500   sca1000 3  0.1
scalar x Sol25    sca1025 3  0.1
scalar x Sol1     sca1001 3  0.1
scalar x Sol50    sca1050 3  0.1
scalar x Sol75    sca1075 3  0.1
overlay x  1 sca1000  sca1025  soiov101
overlay x  1 sca1050  sca1075  soiov102
overlay x  1 sca1001  soiov102 soiov103
overlay x  1 soiov101 soiov103 soiovf10
```

2.2.6. Four scenarios of wind composite model (WCM)

```
overlay x   1      coniin25 soiovf25 cr2525
scalar  x cr2525   cr25251  1        0.01
scalar  x cr25251  final1   1        1
overlay x   3      final1   coni3win wcm1
overlay x   1      coniin25 soiovf20 cr2520
scalar  x cr2520   cr25201  1        0.01
scalar  x cr25201  final2   1        1
overlay x   3      final2   coni3win wcm2
overlay x   1      Coniin20 soiovf15 Cr2015
scalar  x Cr2015   Cr20151  1        0.01
scalar  x Cr20151  final3   1        1
overlay x   3      final3   coni3win wcm3
```

```
overlay x    1      coniin15 soiovf10 cr1510
scalar   x cr1510  cr15101    1      0.01
scalar   x cr15101  final4    1       1
overlay x    3      final4  coni3win  wcm4
```

2.2.7. Potential native woodland according to four scenarios of WCM

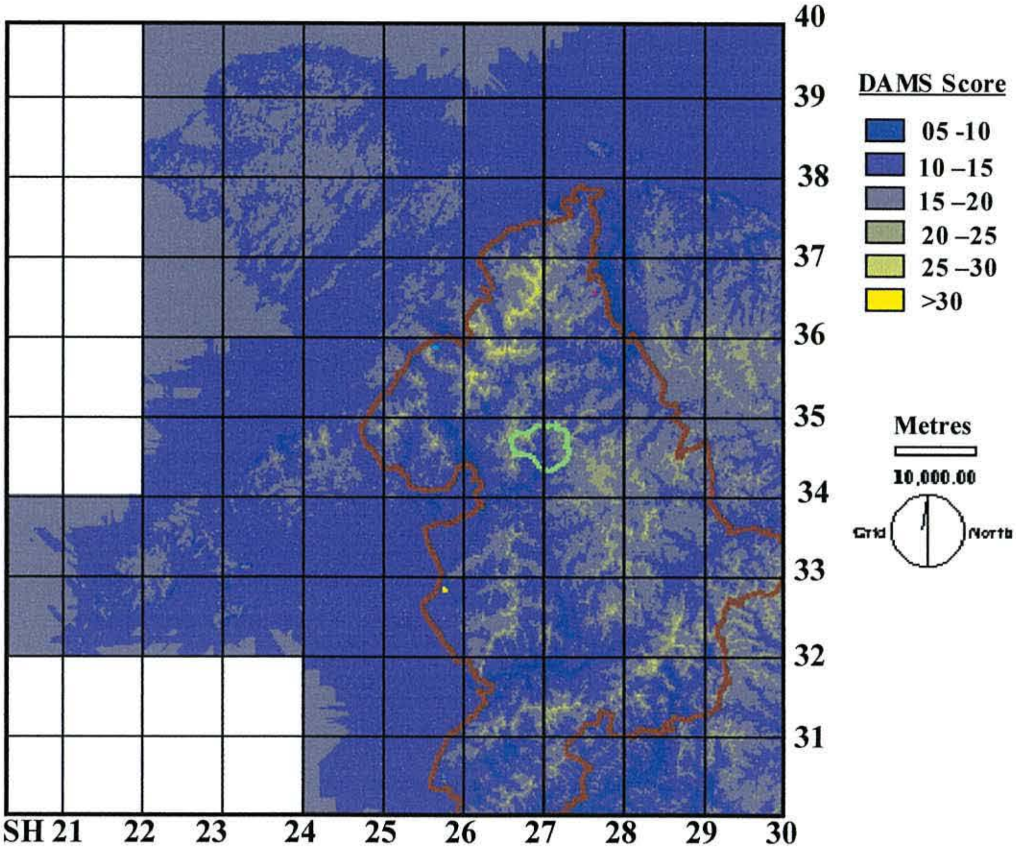
```
reclass x i  wcm1    wcm1re  3  wcm1re
reclass x i  wcm2    wcm2re  3  wcm2re
reclass x i  wcm3    wcm3re  3  wcm3re
reclass x i  wcm4    wcm4re  3  wcm4re
reclass x i wcm1re wcmpot1  3 wcmpot1
reclass x i wcm2re wcmpot2  3 wcmpot2
reclass x i wcm3re wcmpot3  3 wcmpot3
reclass x i wcm4re wcmpot4  3 wcmpot4
reclass  x i wcm1  wcm1uns  2 0 0  25.106 1  25.106 9999 -9999
reclass  x i wcm2  wcm2uns  2 0 0  24.546 1  24.546 9999 -9999
reclass  x i wcm3  wcm3uns  2 0 0  23.968 1  23.968 9999 -9999
reclass  x i wcm4  wcm4uns  2 0 0  23.391 1  23.391 9999 -9999
```

However, correspondence file: *AlAmin* and reclass files: *conioutr*, *rcoutrso, rcouts00, rcouts25, rcouts1, rcouts50, rcouts75, windsnp34, wcm1re, wcm2re, wcm3re, wcm4re, wcmpot1, wcmpot2, wcmpot3 and wcmpot4* are needed to run the model.

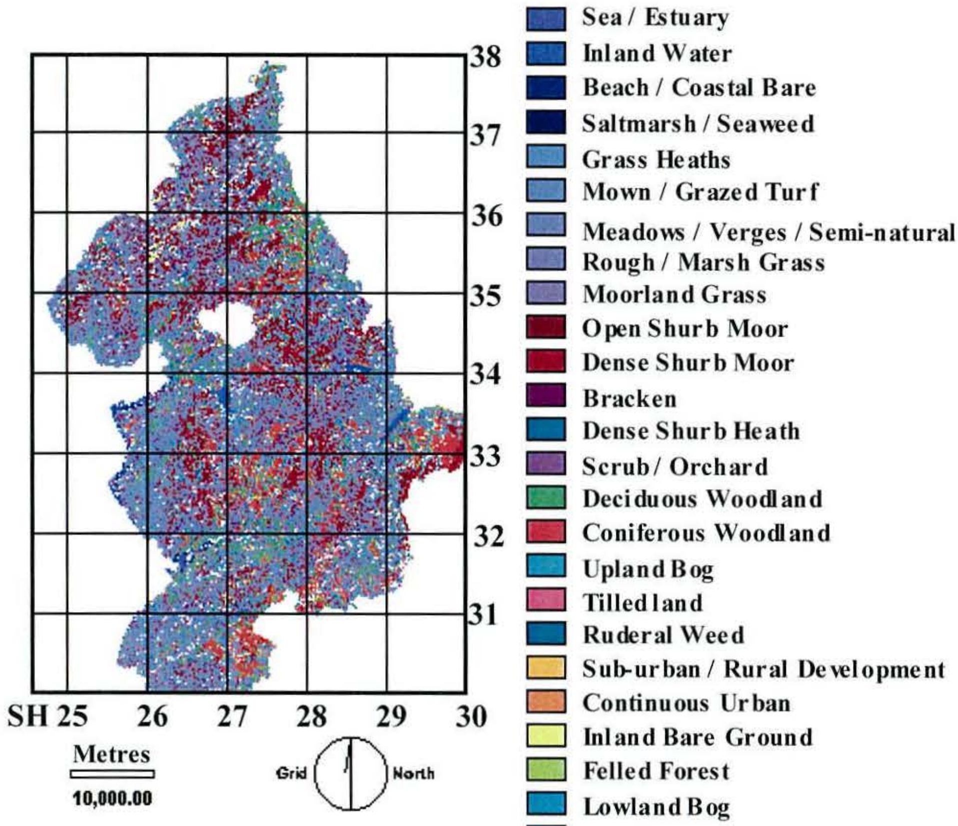
Appendix 2.3

Maps created in simulation of four combination scenarios
of wind composite model (WCM)

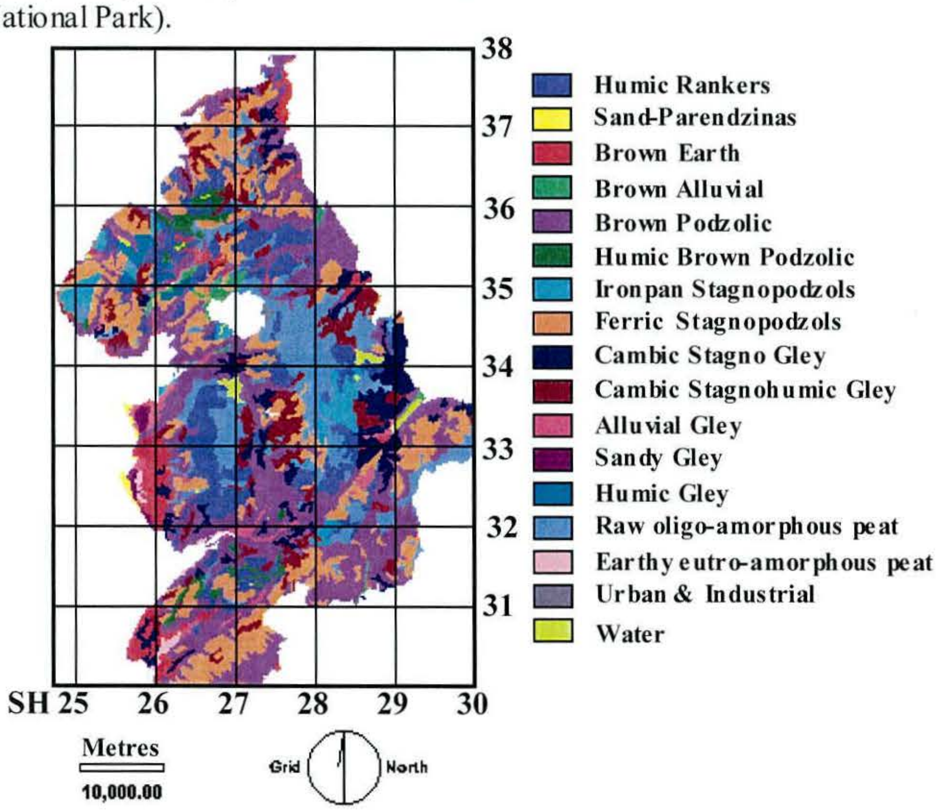
(Method of grid references in all maps was followed by Harley, 1975).



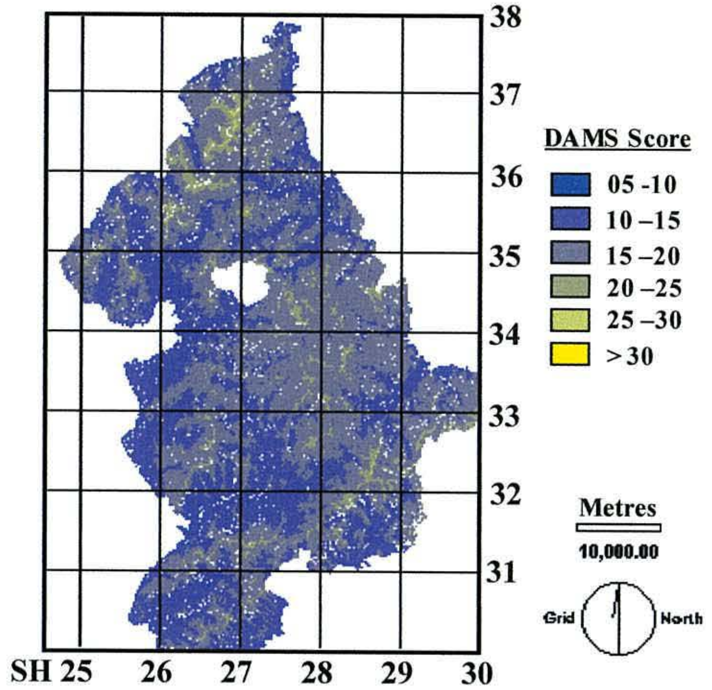
Map A. ***Stfinal1.*** Map created with 20 tiles of maps supplied by the Forestry Commission with CONCAT function of GIS.



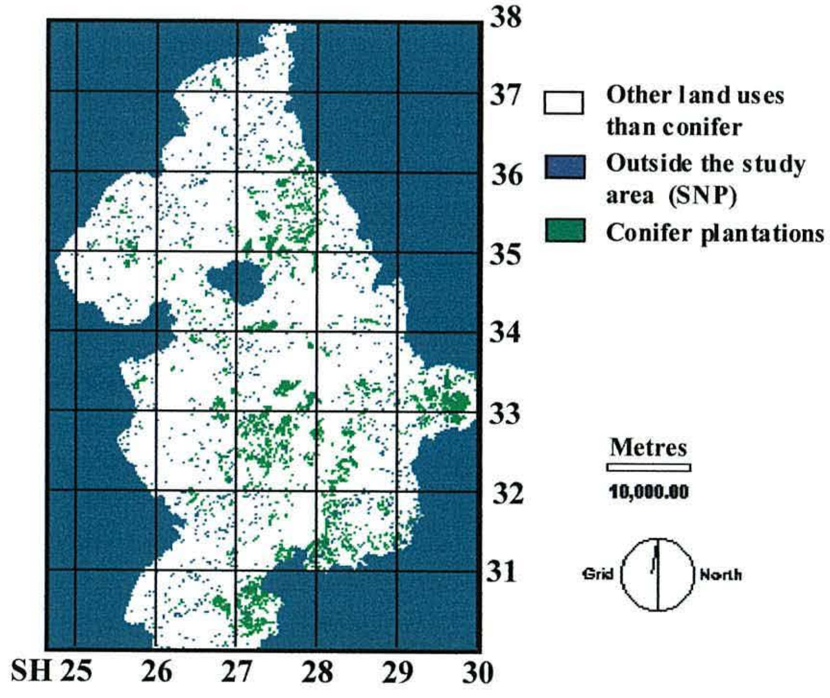
Map B. ***stsnp90***. Land uses in the study area (resampled map of the Snowdonia National Park).



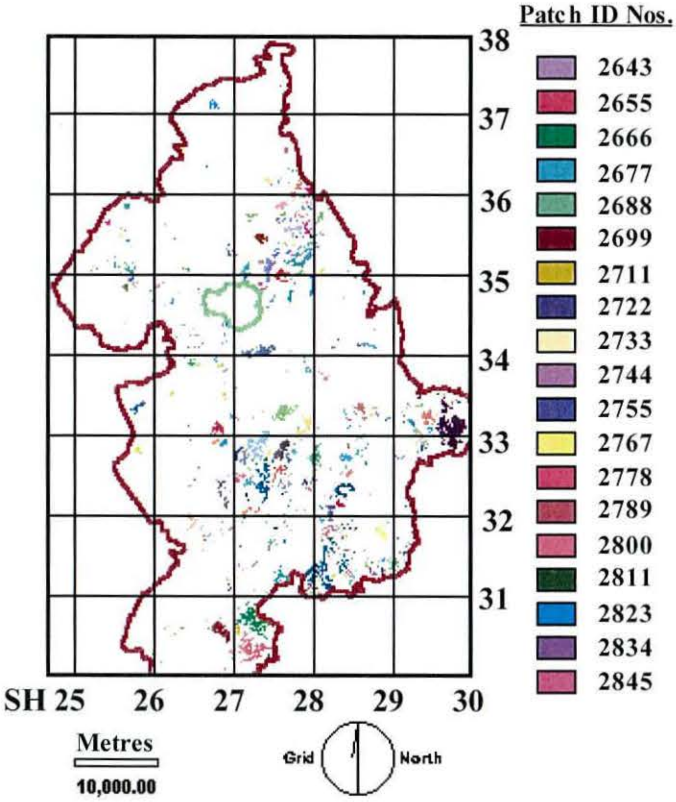
Map C. ***stsnsoil***. Soil classes in the study area.



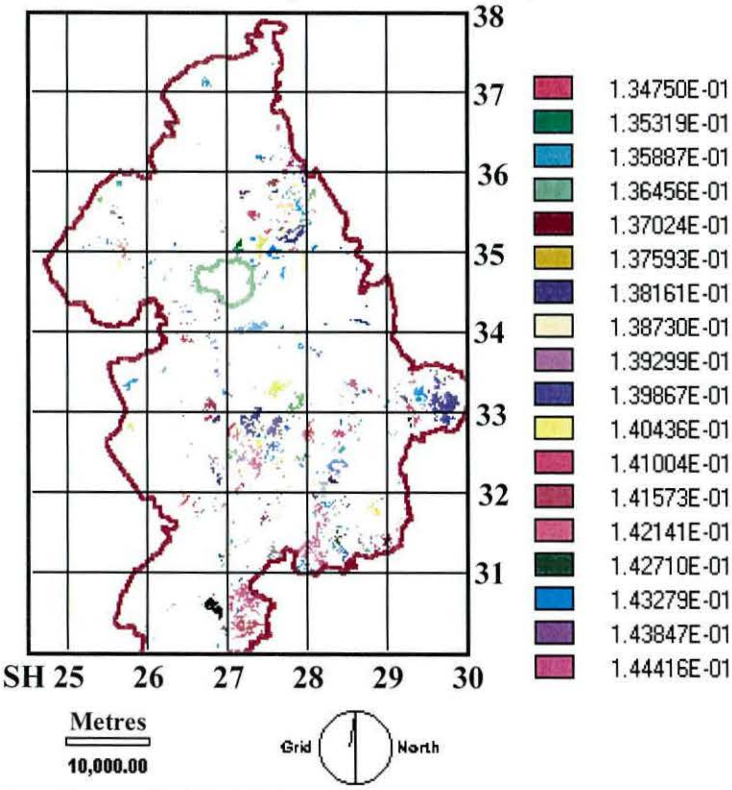
Map D. ***windsnp***. Study area with DAMS data set.



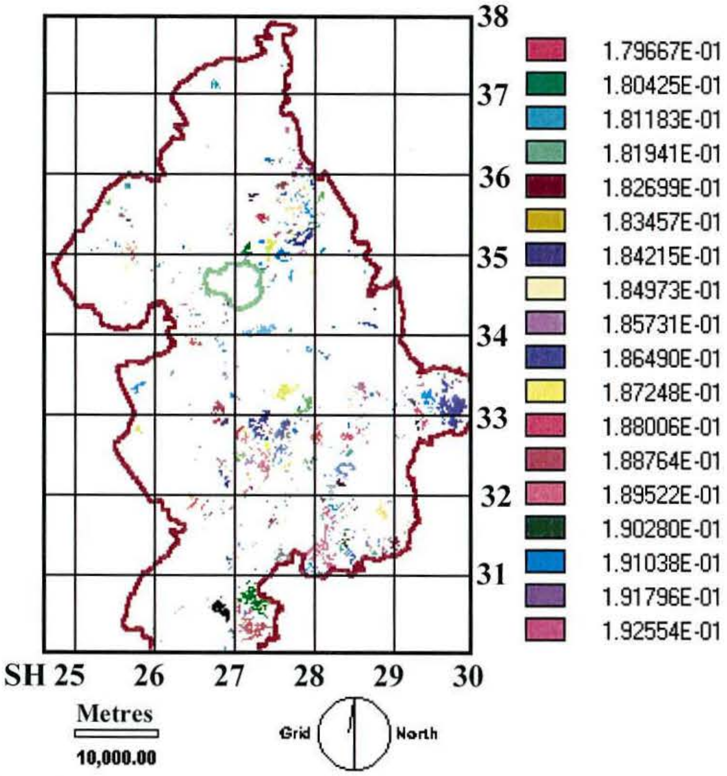
Map E. ***coni4***. FRAGSTATS input map showing conifer patches with green colour.



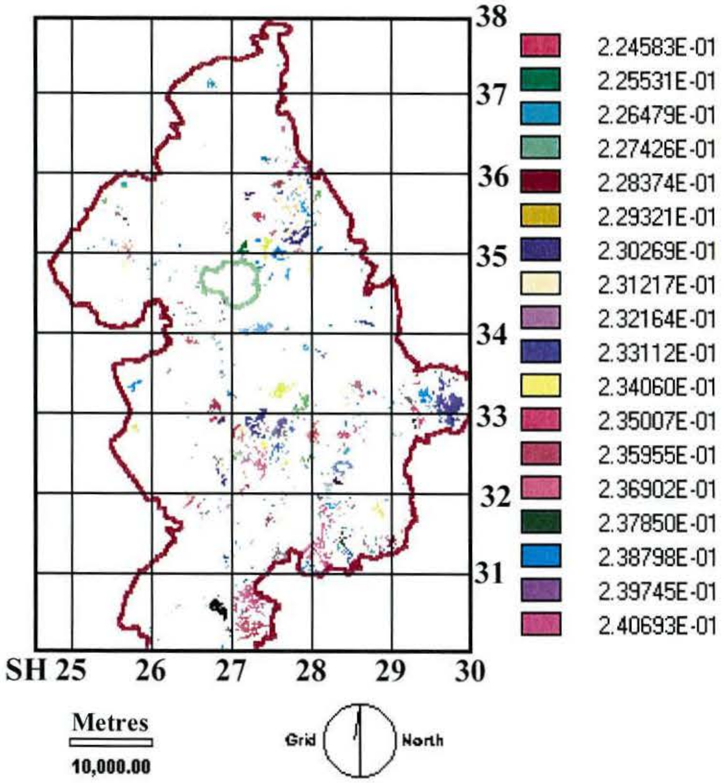
Map F. ***coniout***. FRAGSTAT output map with total 2845 patches in conifer plantations in study area.



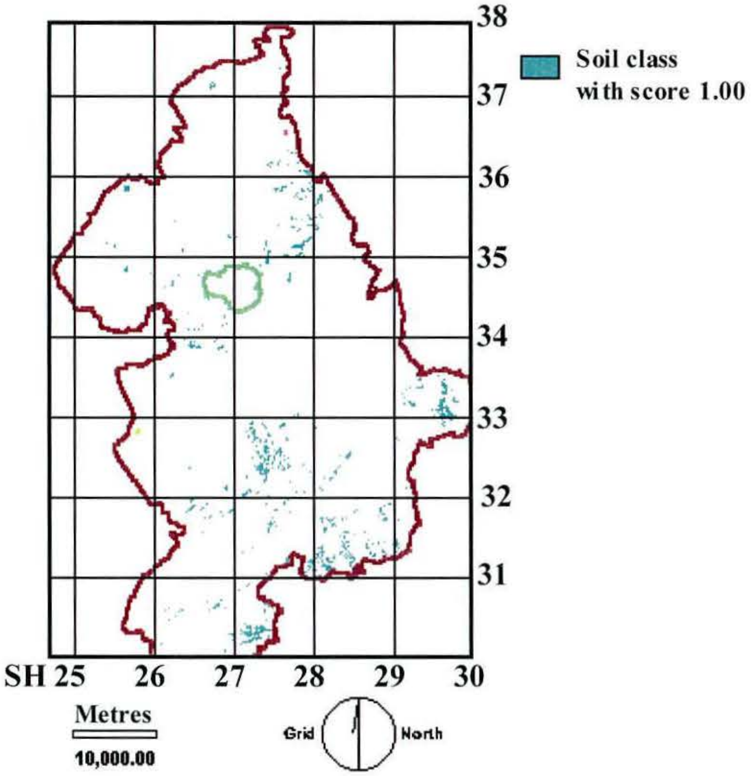
Map G. ***coniin15***. 15% patch shape contribution.



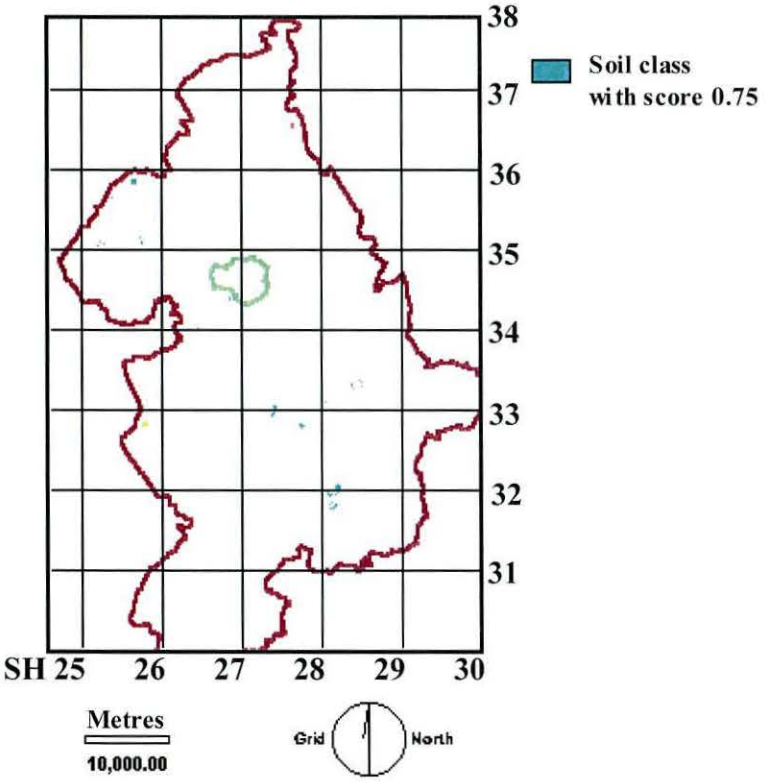
Map H. ***coniin20***. 20% contribution of patch shape



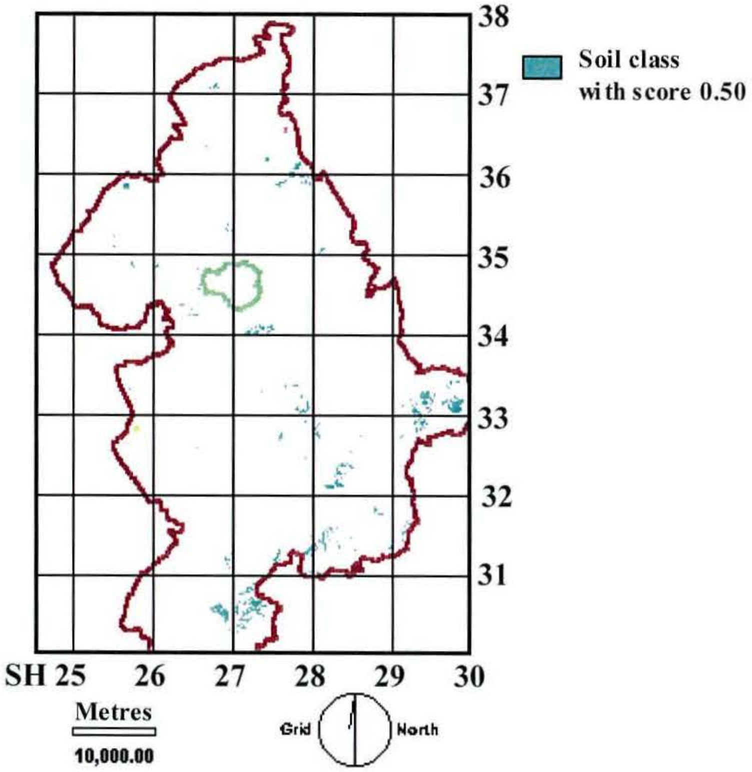
Map I. ***coniin25***. 25% patch contribution



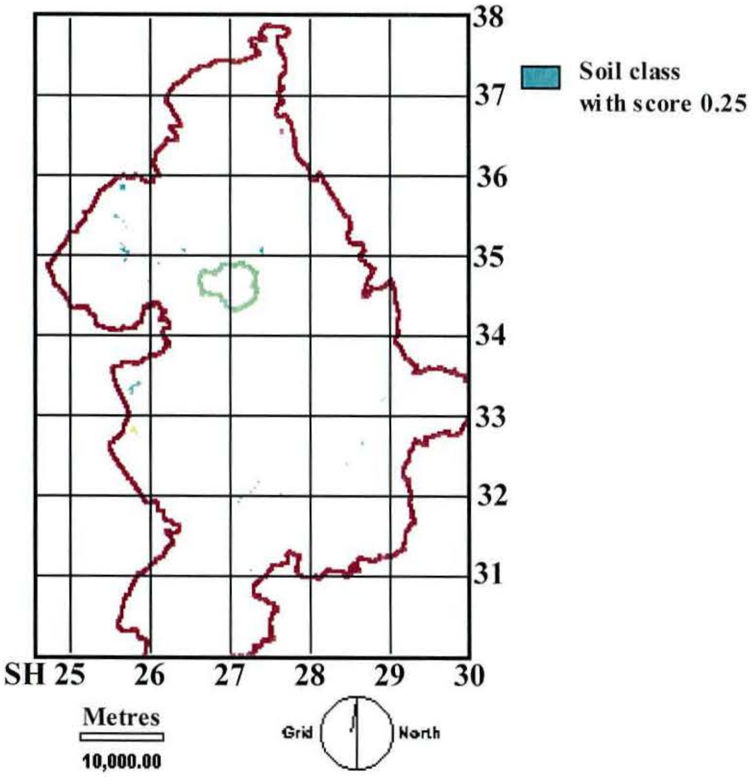
Map J. ***rcouts1***. Reclassified soil class with value 1.00.



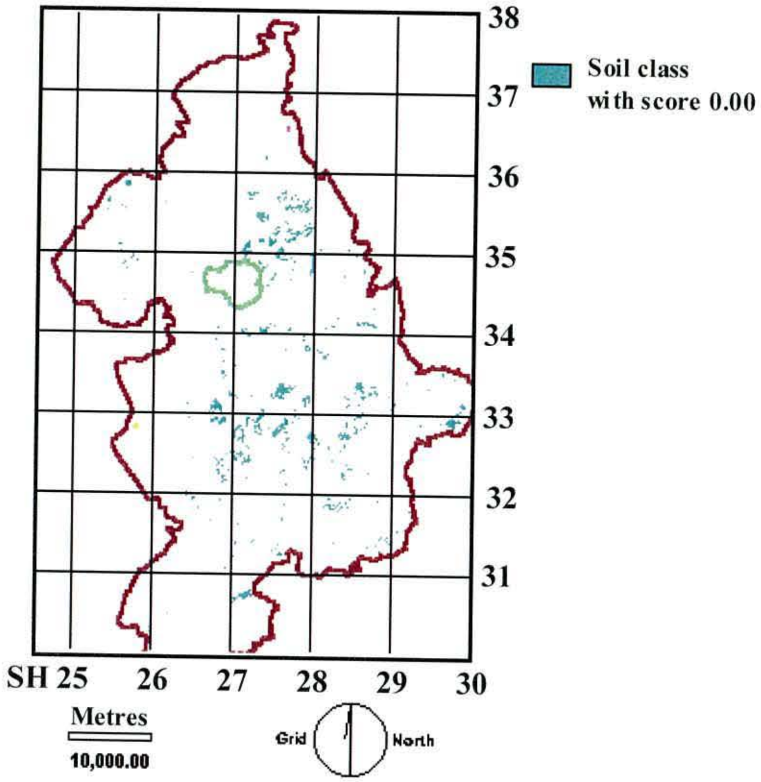
Map K. ***rcouts75***. Reclassified soil class with value 0.75.



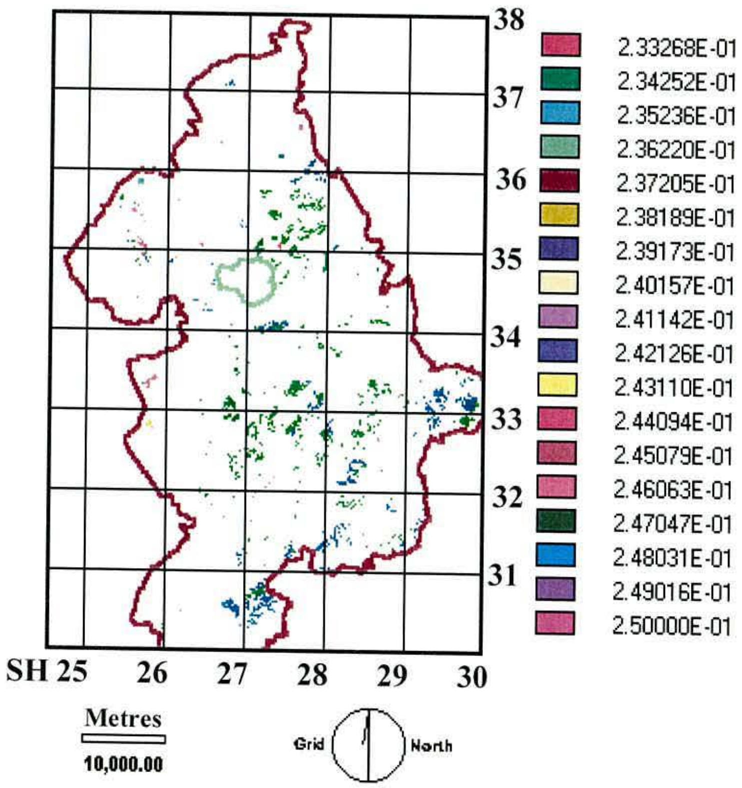
Map L. ***rcouts50***. Reclassified soil class with value 0.50.



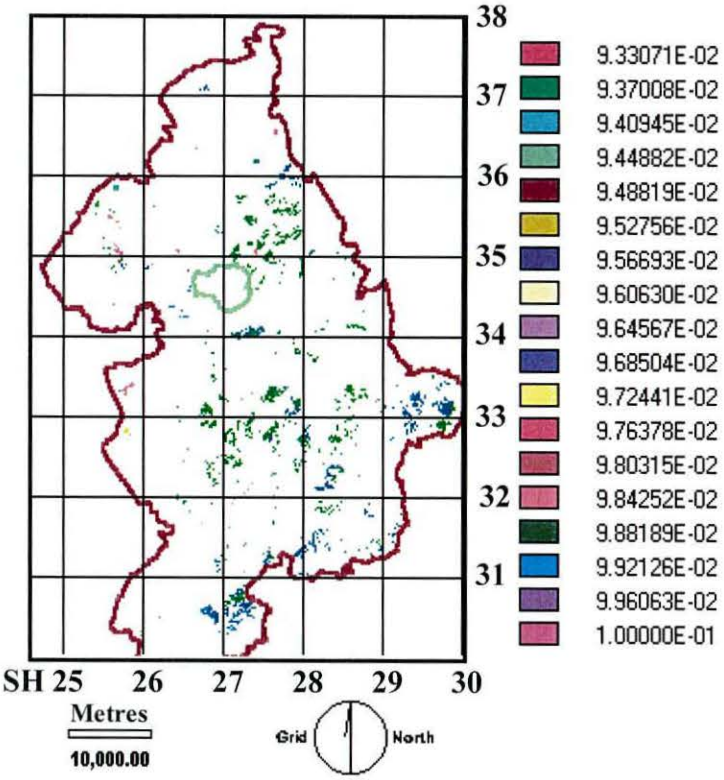
Map M. ***rcouts25***. Reclassified soil class with value 0.25



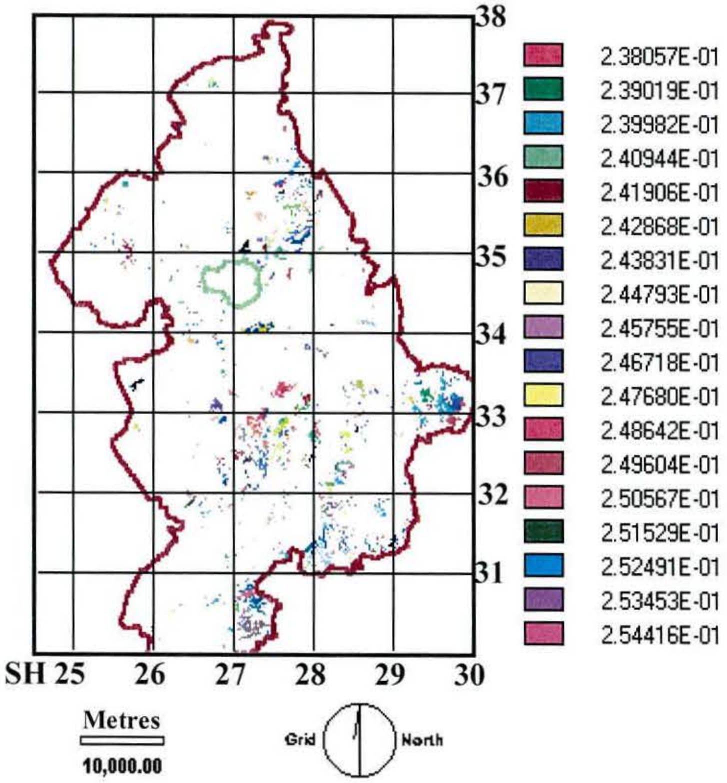
Map N. ***rcouts0***. Reclassified soil class with value 0.00.



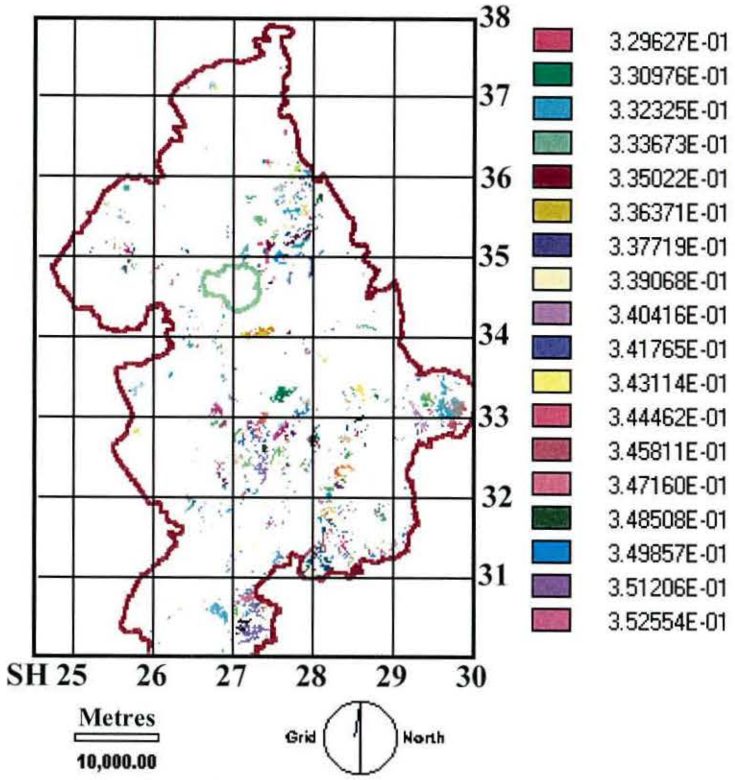
Map O. ***soiovf25***. 25% contribution of soil classes



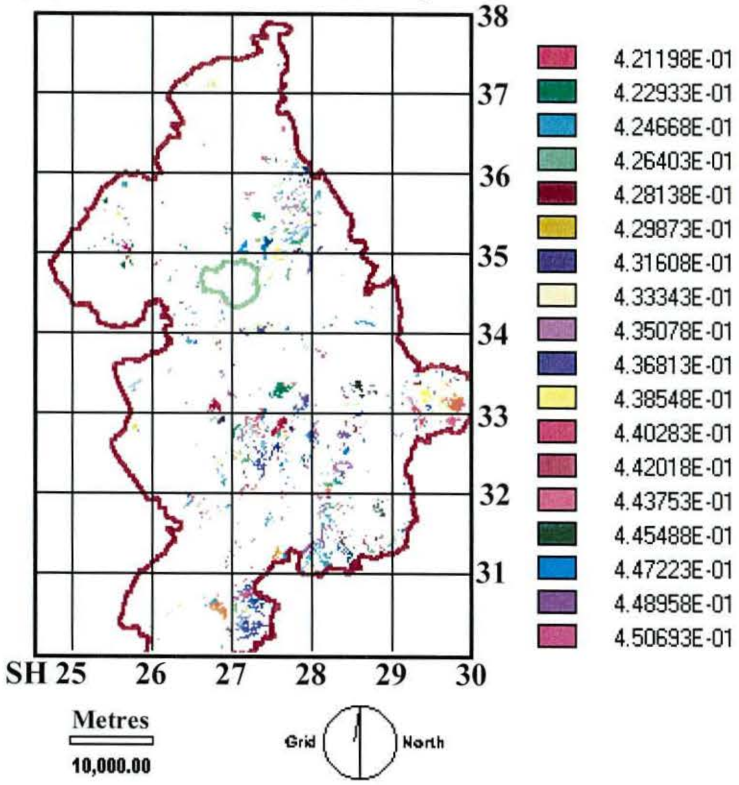
Map P. ***soiovf10***. 10% contribution of soil classes



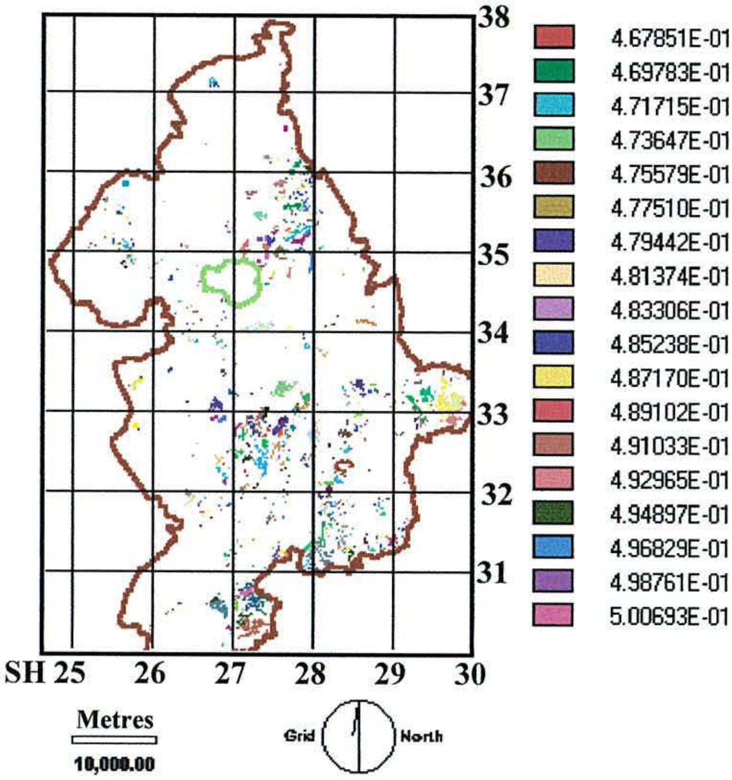
Map Q. ***cr15101***. Map with contribution of leaf presence with contributions of 15% patch shape, 10% soil classes in the study area.



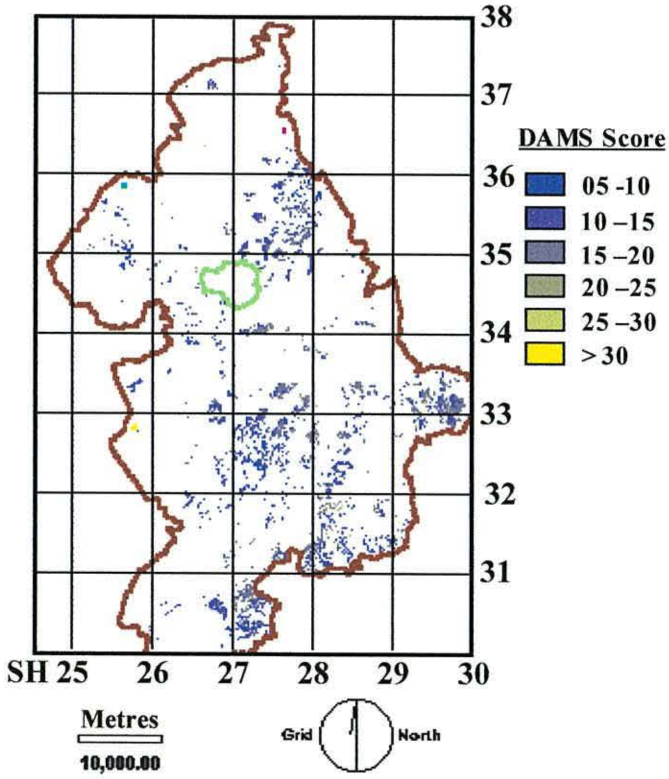
Map R. ***cr20151***. Contribution of leaf presence with contributions of 20% patch shape, 15% soil classes in the study area.



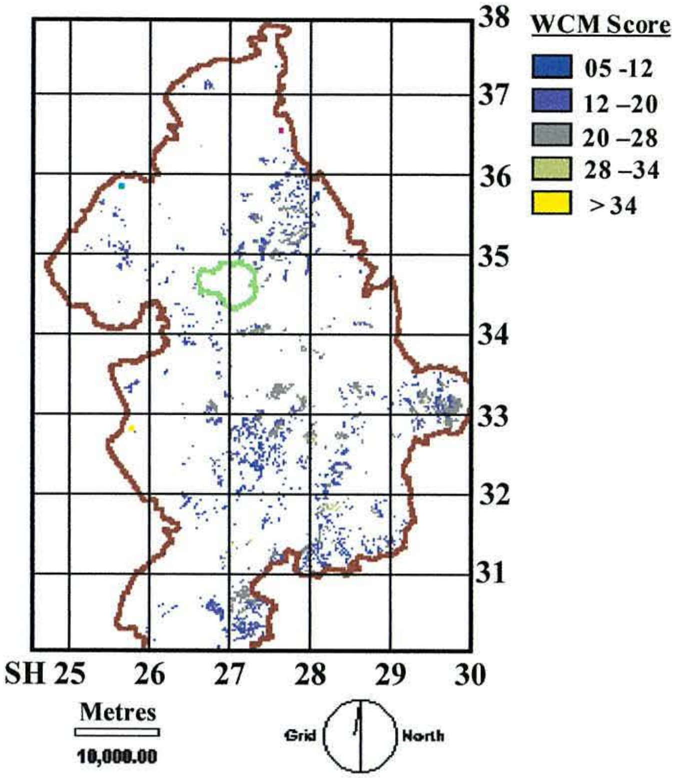
Map S. ***cr25201***. Contribution of leaf presence with contributions of 25% patch shape, 20% soil classes in the study area.



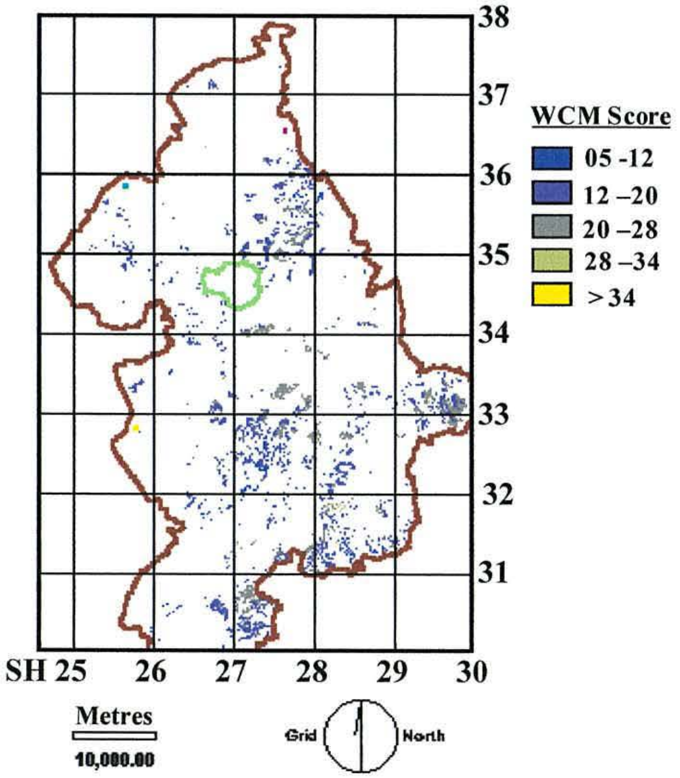
Map T. ***cr25251***. Contribution of leaf presence with contributions of 25% patch shape, 25% soil classes in the study area.



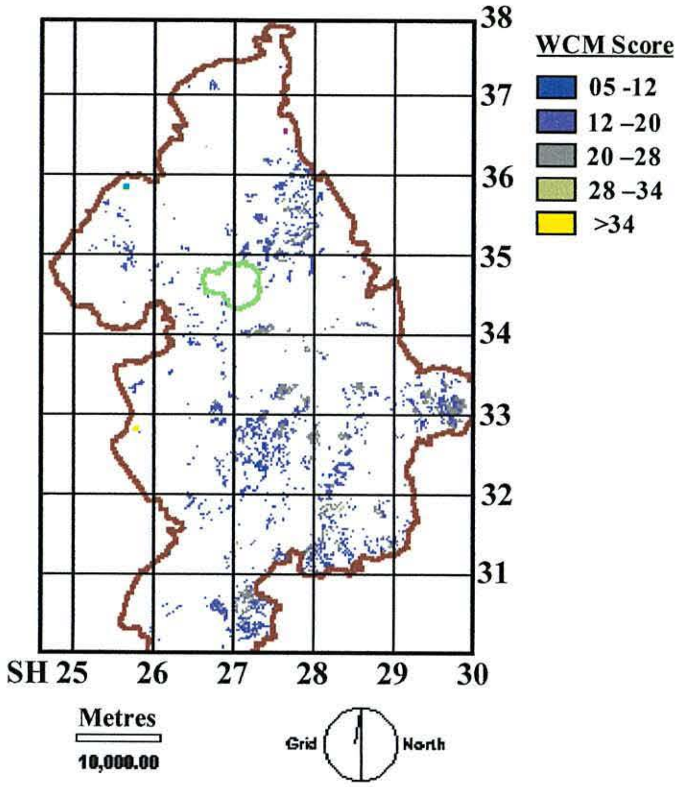
Map U. ***coni3win.*** DAMS data for the conifer plantations of the study area..



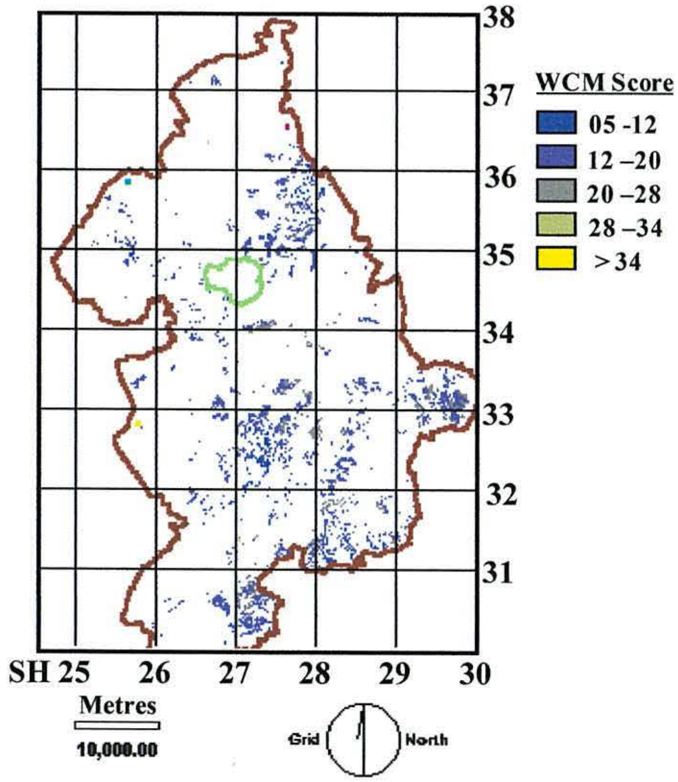
Map V. ***WCM1.*** Wind Composite model with combination scenario 1



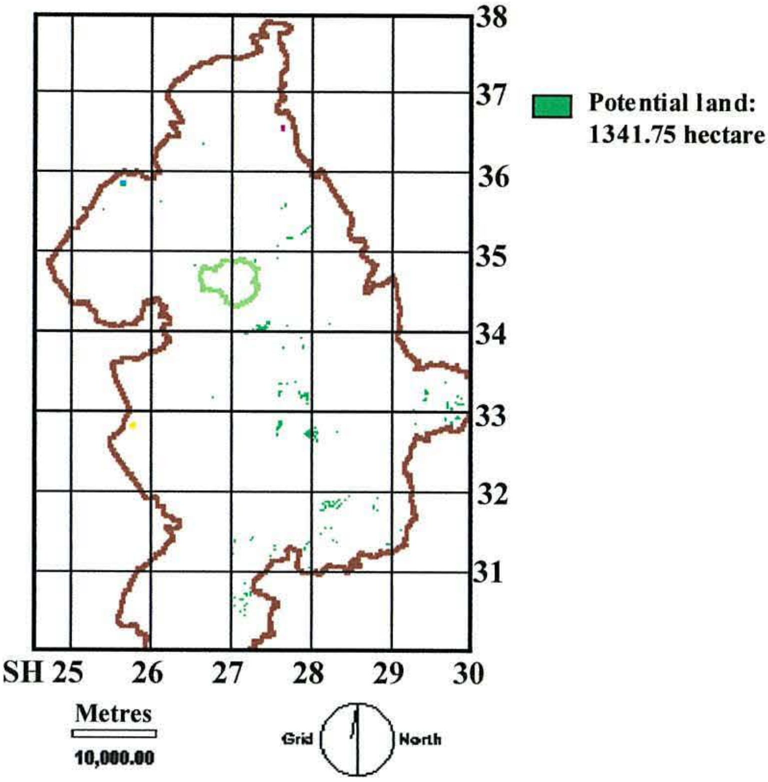
Map W. ***WCM2.*** Wind Composite model with combination scenario 2



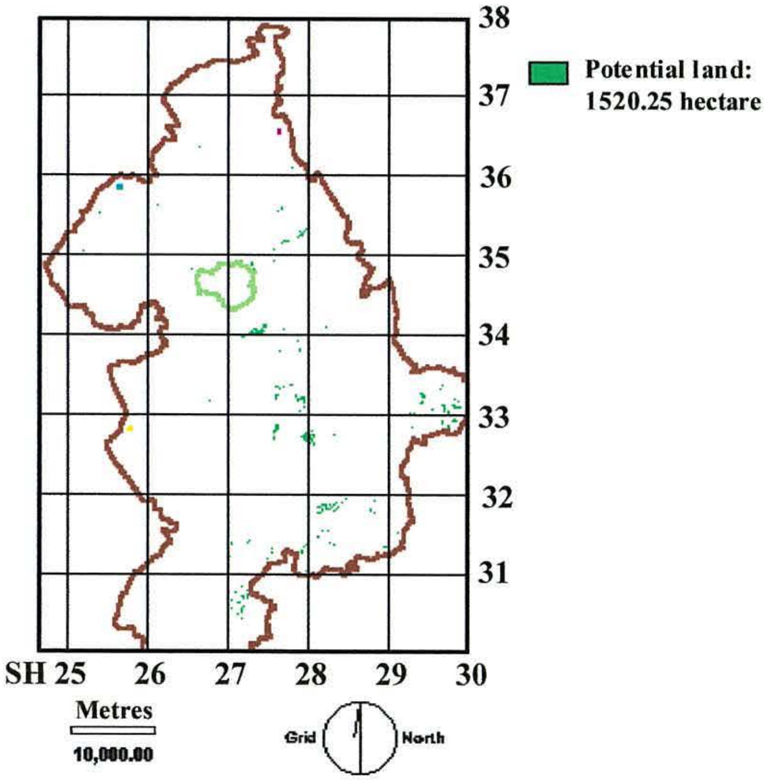
Map X. *WCM3.* Wind Composite model with combination scenario 3



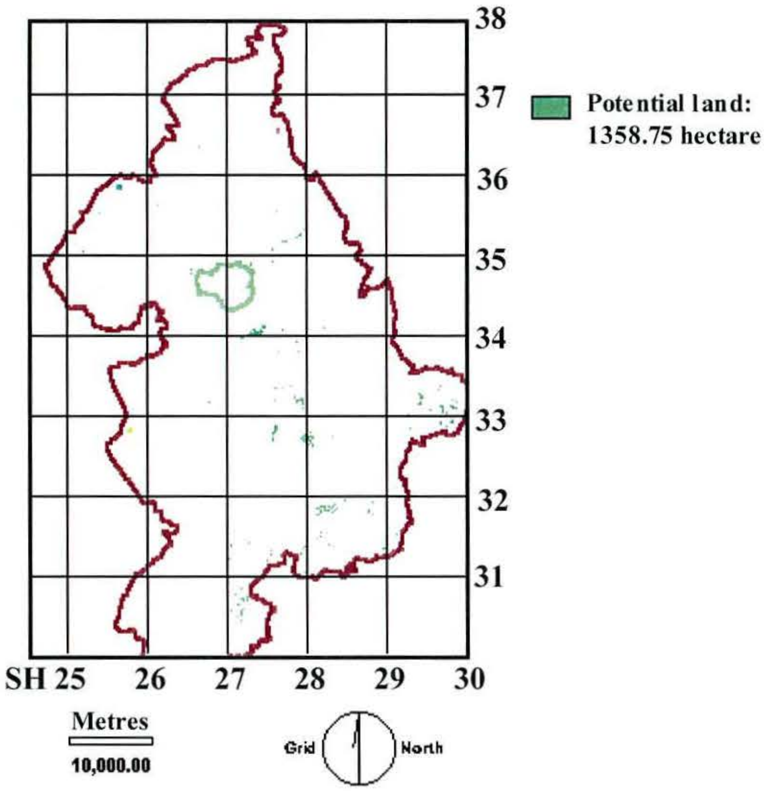
Map Y. *WCM4.* Wind Composite model with combination scenario 4



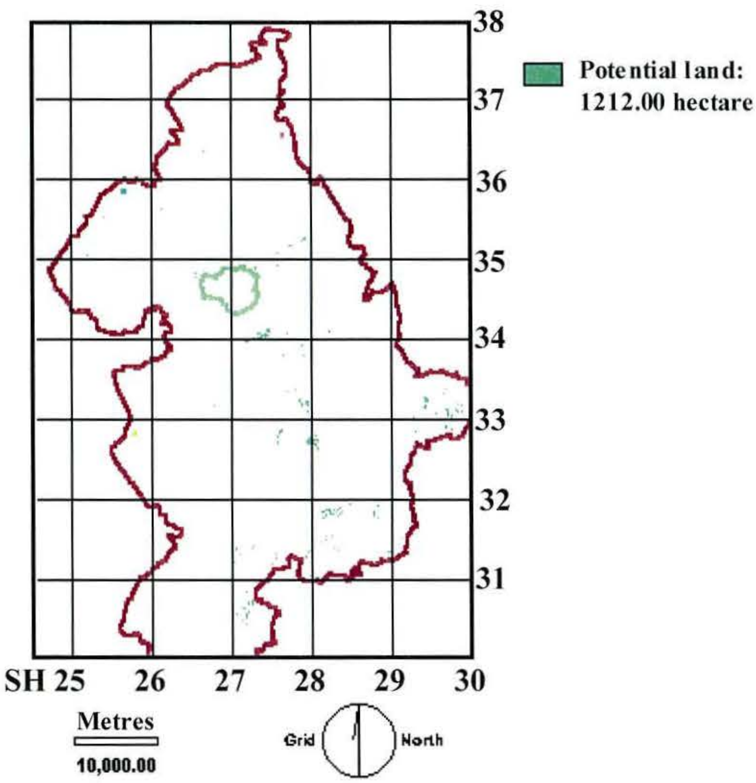
Map Z. ***wcm1pot.*** Potential native broadleaved woodland area with combination scenario 1 of WCM



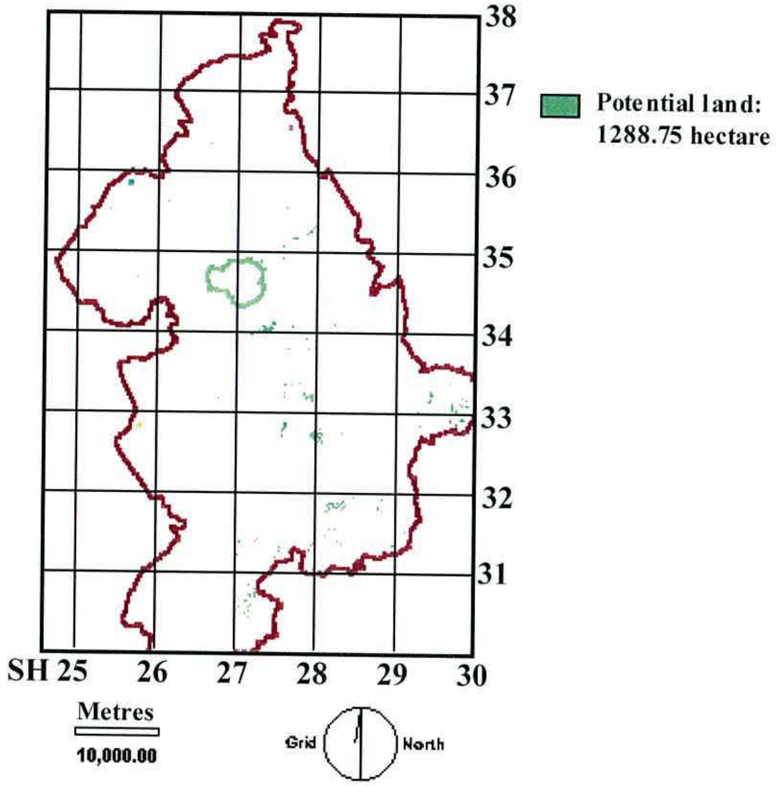
Map AA. ***wcm2pot.*** Potential native broadleaved woodland area with combination scenario 2 of WCM



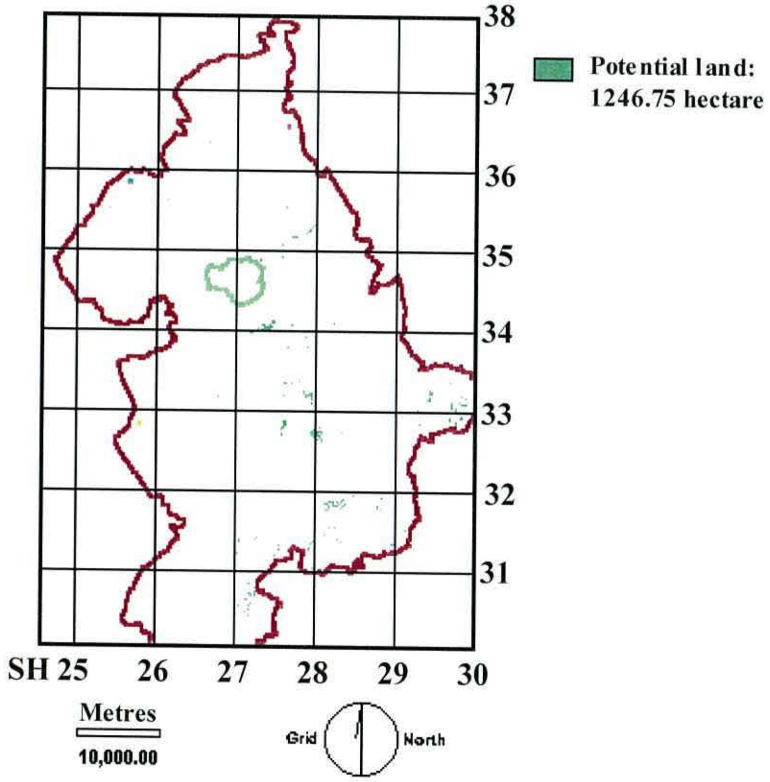
Map AB. ***wcm3pot.*** Potential native broadleaved woodland area with combination scenario 3 of WCM



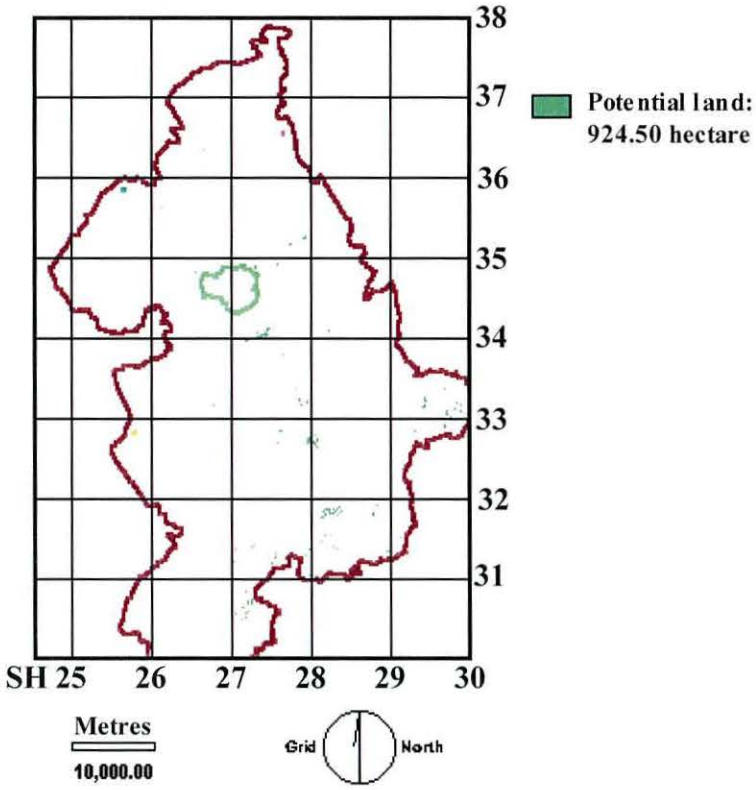
Map AC. ***wcm4pot.*** Potential native broadleaved woodland area with combination scenario 4 of WCM



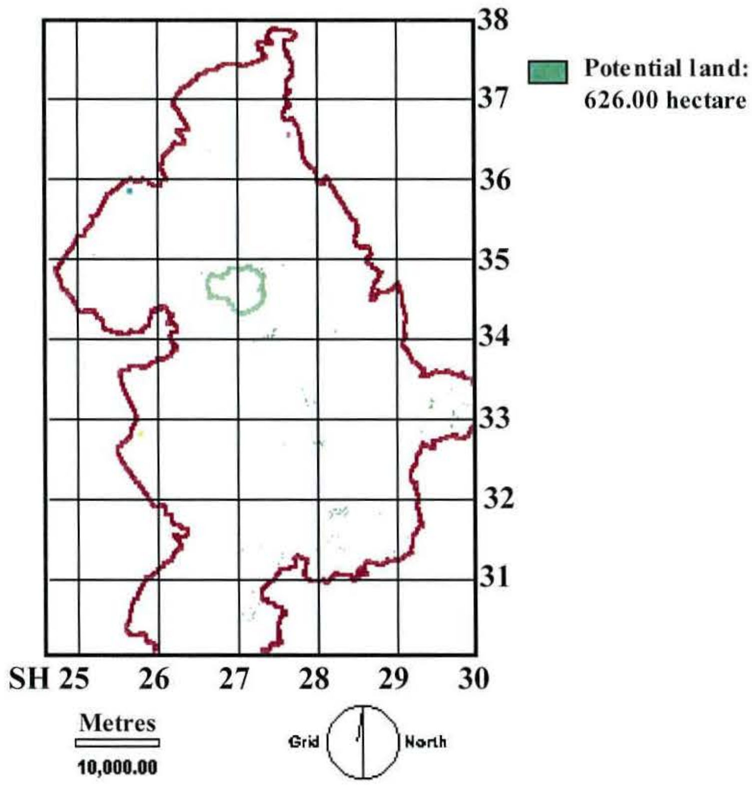
Map AD. ***wcm1uns.*** Location of lands over suitable limit of Sitka spruce with scenario 1 of WCM



Map AE. ***wcm2uns.*** Location of lands over suitable limit of Sitka spruce with scenario 2 of WCM



Map AF. ***wcm3uns.*** Location of lands over suitable limit of Sitka spruce with scenario 3 of WCM



Map AG. ***wcm4uns.*** Location of lands over suitable limit of Sitka spruce with scenario 4 of WCM

Appendix: 2.4

Names of the species discussed in the Ecological Site Classification for Forestry in Great Britain (Pyatt and Suárez, 1997)

Abbr.	Local Name	Scientific name
1. SP	SCOTS PINE	*Pinus sylvestris*
2. CP	CORSICAN PINE	*Pinus nigra, P. laricio*
3. LP	LODGEPOLE PINE	*Pinus contorta*
4. SS	SITKA SPRUCE	*Picea sitchensis*
5. NS	NORWAY SPRUCE	*Picea abies*
6. EL	EUROPEAN LARCH	*Larix decidua*
7. JL	JAPANESE LARCH	*Larix kaempferi*
8. DF	DOUGLAS FIR	*Pseudotsuga menziesii*
9. GF	GRAND FIR	*Abies grandis*
10. NF	NOBLE FIR	*Abies procera*
11. WH	WESTERN HEMLOCK	*Tsuga heterophylla*
12. RC	WESTERN RED CEDAR	*Thuja plicata*
13. SOK	SESSILE OAK	*Quercus petraea*
14. POK	PEDUNCULATE OAK	*Quercus robur*
15. BE	BEECH	*Fagus sylvatica*
16. AH	ASH	*Fraxinus excelsior*
17. SY	SYCAMORE	*Acer pseudoplatanus*
18. WEM	WYCH ELM	*Ulmus glabra*
19. SBI	SILVER BIRCH	*Betula pendula*
20. DBI	DOWNY BIRCH	*Betula pubescens*
21. ASP	ASPEN	*Populus tremula*
22. CAR	COMMON ALDER	*Alnus glutinosa*
23. NOM	NORWAY MAPLE	Acer *platanoides*
24. WCH	GEAN, WILD CHERRY	*Prunus avium*
25. PO	POPLAR CULTIVARS	*Populus deltoides, P.nigra, P. trichocarpa*

Appendix: 2.5

Soil classes of the Snowdonia National Park and their relative scores

Soil type	Soil code	Score
Brown Earths Brown Alluvial	1, 1d, 1u, 1z	1.00
Podzols	3	1.00
Intergrade and Podzolic Ironpan soils Brown Podzolic Humic Brown Podzolic	4b, 4z	1.00
Ironpan soils Ironpan Stagnopodzols	4	0.75
Ground water gley Allvial Gley Sandy Gley	5	0.25
Peaty Gleys	6	0.00
Peaty Podzolic Gleys Humic Gley	6z	0.25
Brown Gleys and Pozolic Gleys Ferric Stagnopodzols	7b, 7z	0.50
Surface Water Gleys Cambic Stagno Gley Cambic Stagnohumic Gley	7	0.00
Juncus Bogs	8a, 8b, 8c, 8d	0.00
Molinia Bogs	9a, 9b, 9c, 9d, 9e	0.00
Sphagnum Bogs Raw Oligo-amorphous Peat Earthy eutro-amorphous Peat	10a, 10b	0.00
Calluna / Eriophorum / Trichophorum Bogs	11a, 11b, 11c, 11d	0.00
Eroded Bogs	14, 14h, 14w	0.00
Mining spoil, stony or coarse textured	2s	1.00
Mining spoil, shaly or coarse textured	2m	0.50
Calcareous (Rendzina) Sand Parendzinas	12a	0.50
Calcarious (Argillic brown earths)	12b, 12t	1.00
Brown and Podzolic Rankers	13b, 13z	0.25-0.00
Scree	13s	0.00
Peaty and Gley Rankers Humic Rankers	13r, 13g, 13p	0.00
Well Drained Littoral Soils	15s, 15d, 15w	1.00

Appendix 2.6

Example about the patch matrices derived by the FRAGSTATS in the ***coniout*** image.

LID	PID	TYPE	AREA Hectare	LSIM	PERIM meter	SHAPE	FRACT	CORE	NCORE	CAI	NEAR
frag4	1	NULL	0.5	100	300	1.06	1.01	0	0	0	223.61
frag4	2	NULL	0.5	100	400	1.41	1.08	0	0	0	50
frag4	3	NULL	0.25	100	200	1	1	0	0	0	1000
frag4	4	NULL	0.25	100	200	1	1	0	0	0	50
frag4	5	NULL	0.25	100	200	1	1	0	0	0	111.8
frag4	6	NULL	0.75	100	400	1.15	1.03	0	0	0	50
frag4	7	NULL	0.5	100	300	1.06	1.01	0	0	0	100
frag4	8	NULL	0.25	100	200	1	1	0	0	0	50
frag4	9	NULL	0.25	100	200	1	1	0	0	0	304.14
frag4	10	NULL	0.25	100	200	1	1	0	0	0	50
frag4	11	NULL	0.25	100	200	1	1	0	0	0	50
frag4	12	NULL	0.25	100	200	1	1	0	0	0	70.71
frag4	13	NULL	0.25	100	200	1	1	0	0	0	618.47
frag4	14	NULL	1.75	100	700	1.32	1.06	0	0	0	50
frag4	15	NULL	0.75	100	500	1.44	1.08	0	0	0	450
frag4	16	NULL	0.5	100	300	1.06	1.01	0	0	0	50
frag4	17	NULL	1.75	100	900	1.7	1.11	0	0	0	50
frag4	18	NULL	0.25	100	200	1	1	0	0	0	70.71
frag4	19	NULL	0.5	100	300	1.06	1.01	0	0	0	70.71
frag4	20	NULL	0.75	100	500	1.44	1.08	0	0	0	100
frag4	21	NULL	0.5	100	400	1.41	1.08	0	0	0	111.8
frag4	22	NULL	0.75	100	400	1.15	1.03	0	0	0	100
frag4	23	NULL	0.25	100	200	1	1	0	0	0	141.42
frag4	24	NULL	0.25	100	200	1	1	0	0	0	1096.59
frag4	25	NULL	3.5	100	1400	1.87	1.12	0	0	0	50
frag4	26	NULL	0.75	100	400	1.15	1.03	0	0	0	890.22
frag4	27	NULL	0.5	100	400	1.41	1.08	0	0	0	50
frag4	28	NULL	3.25	100	1200	1.66	1.1	0	0	0	111.8
frag4	29	NULL	82.5	100	11000	3.03	1.16	5.5	4	6.67	111.8
frag4	30	NULL	1.25	100	500	1.12	1.02	0	0	0	50
frag4	31	NULL	0.25	100	200	1	1	0	0	0	50
frag4	32	NULL	2.5	100	1000	1.58	1.09	0	0	0	602.08
frag4	33	NULL	0.75	100	400	1.15	1.03	0	0	0	50
frag4	34	NULL	2	100	900	1.59	1.09	0	0	0	50
frag4	35	NULL	0.25	100	200	1	1	0	0	0	403.11
frag4	36	NULL	0.25	100	200	1	1	0	0	0	111.8
frag4	37	NULL	0.75	100	400	1.15	1.03	0	0	0	626.5
frag4	38	NULL	0.5	100	300	1.06	1.01	0	0	0	111.8
frag4	39	NULL	0.25	100	200	1	1	0	0	0	626.5
frag4	40	NULL	0.25	100	200	1	1	0	0	0	1724.09
frag4	41	NULL	0.75	100	500	1.44	1.08	0	0	0	1662.08
frag4	42	NULL	5.5	100	1600	1.71	1.1	0	0	0	50
frag4	43	NULL	0.5	100	300	1.06	1.01	0	0	0	50
frag4	44	NULL	17	100	3800	2.3	1.14	0.5	1	2.94	984.89

Appendix 3.3.1: Illustrating the flow diagrams of GIS procedures followed for organic carbon model.

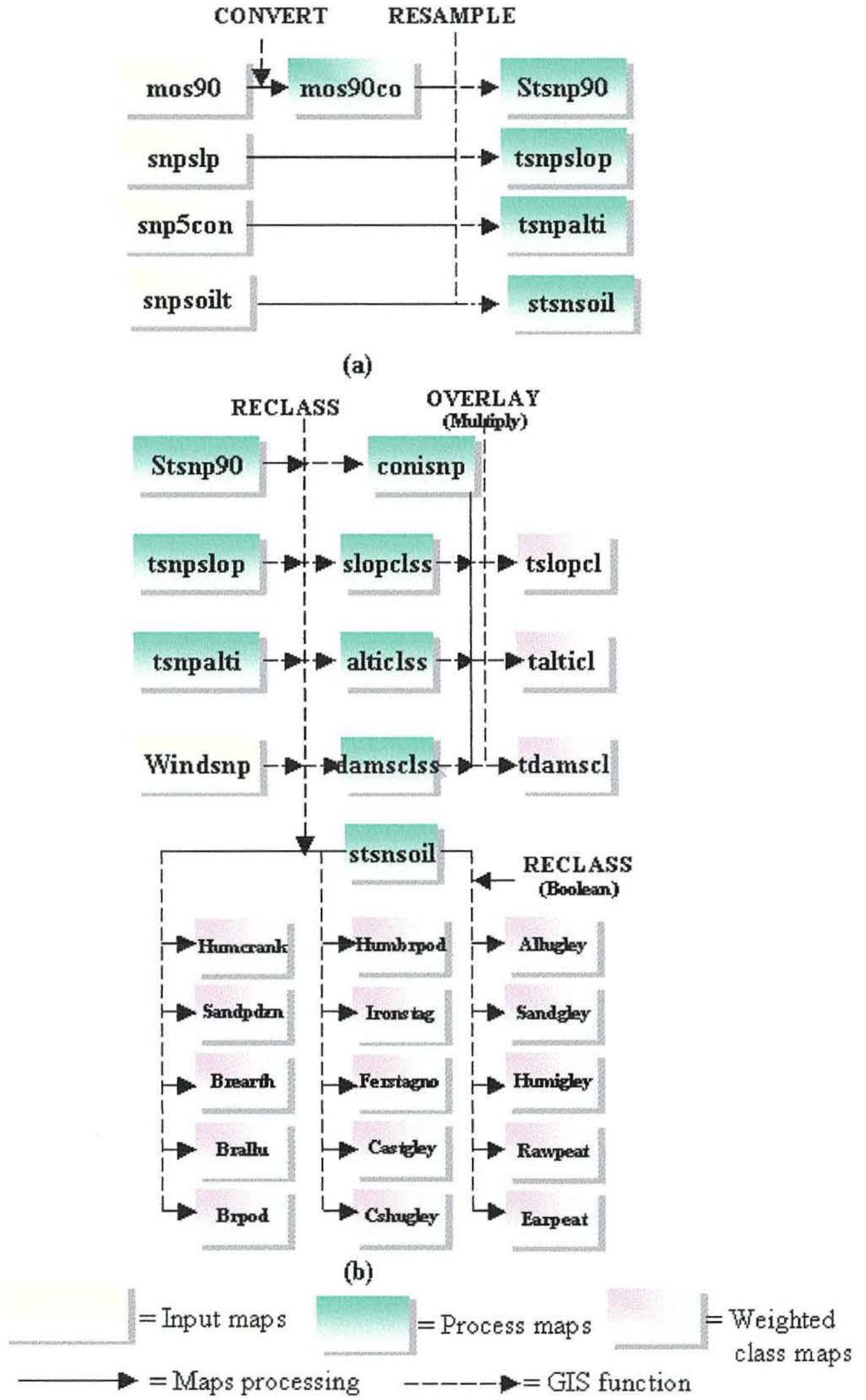


Figure 3.3.1.1 GIS procedures followed in input, process 1 and 2 stages. (a) showing the procedure of geo register for main input maps and (b) illustrating the creation of main (for estimating yield) classes considered in the study.

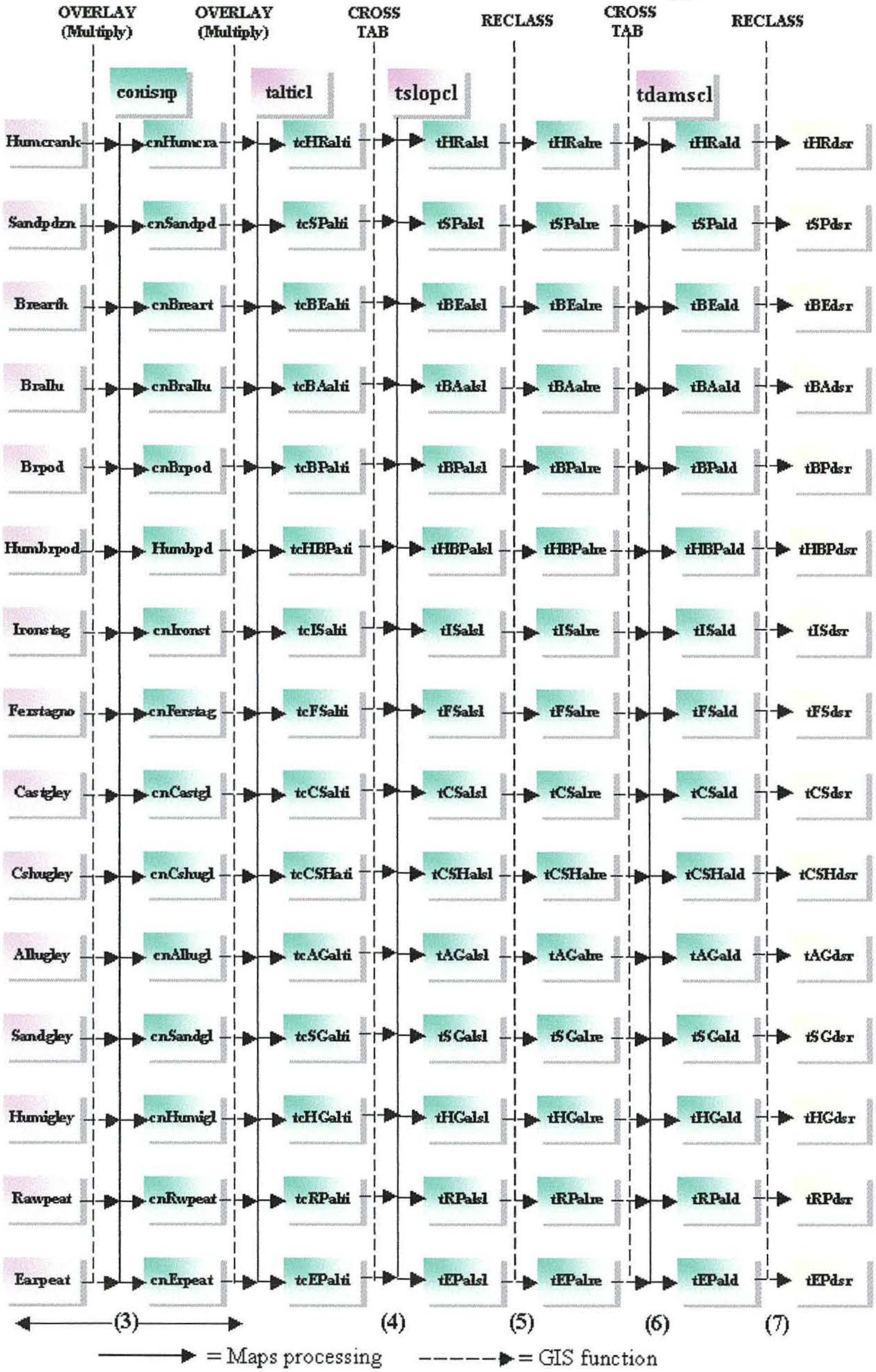
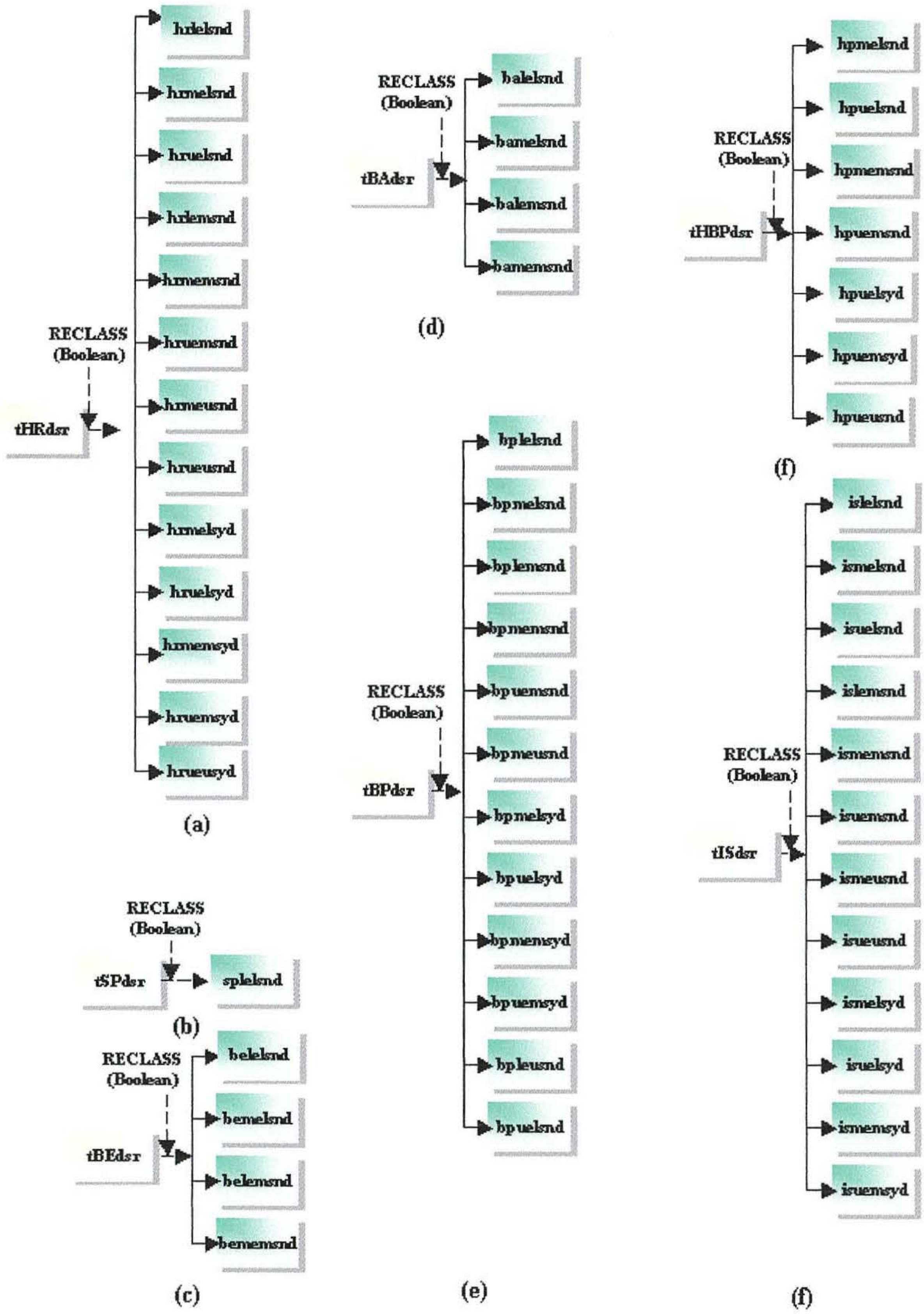


Figure 3.3.1.2 GIS procedures followed in process 3, 4,5, 6 and 7 stage.



——▶ = Maps processing - - - - -▶ = GIS function

Figure 3.3.1.3 GIS procedures followed in AYC 1 stage. Sites are classified with Weight of soil, altitude, slope and exposure to wind. (continue)

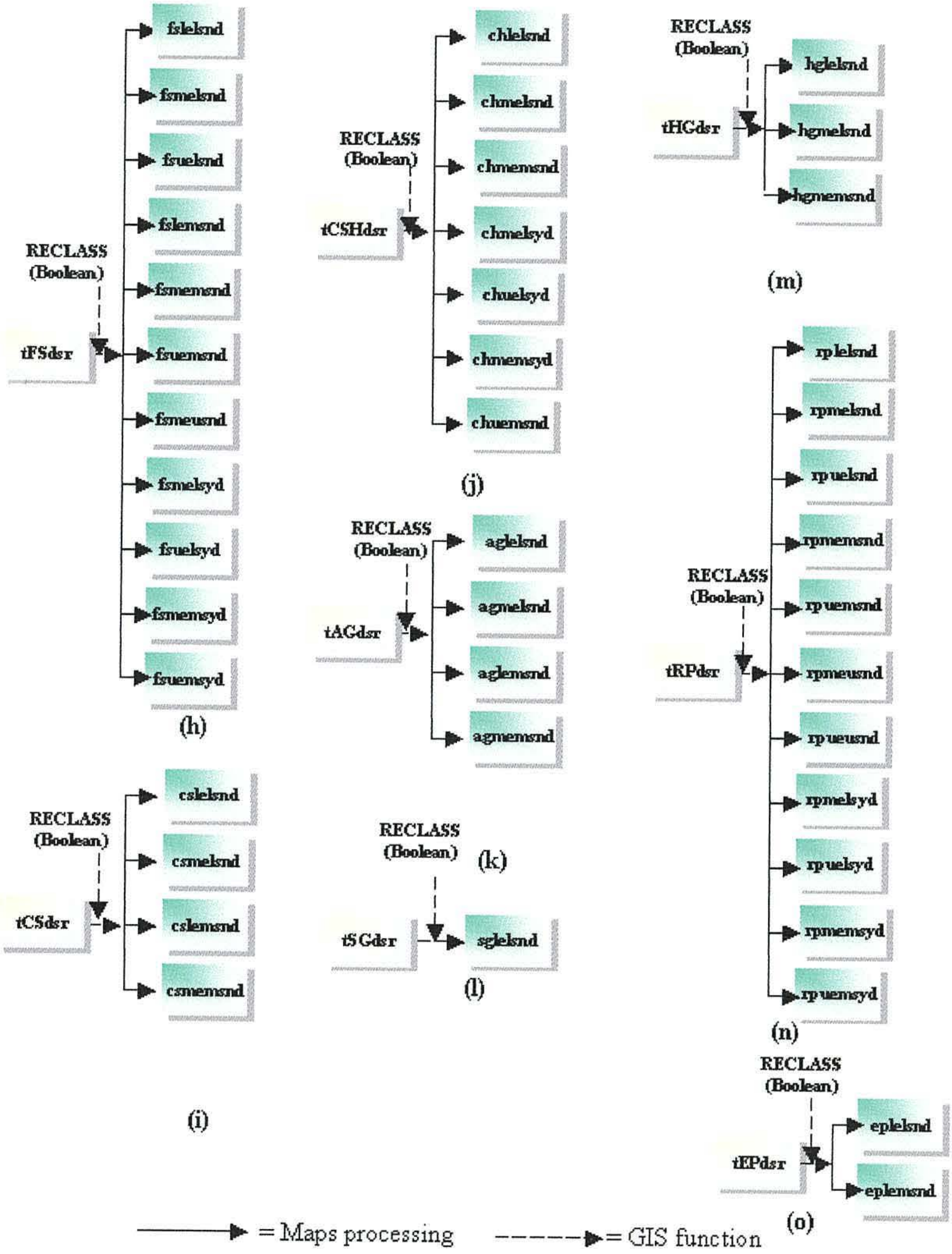


Figure 3.3.1.3 (Continue) GIS procedures followed in AYC 1 stage. Sites are classified with weight of soil, altitude, slope and exposure to wind.

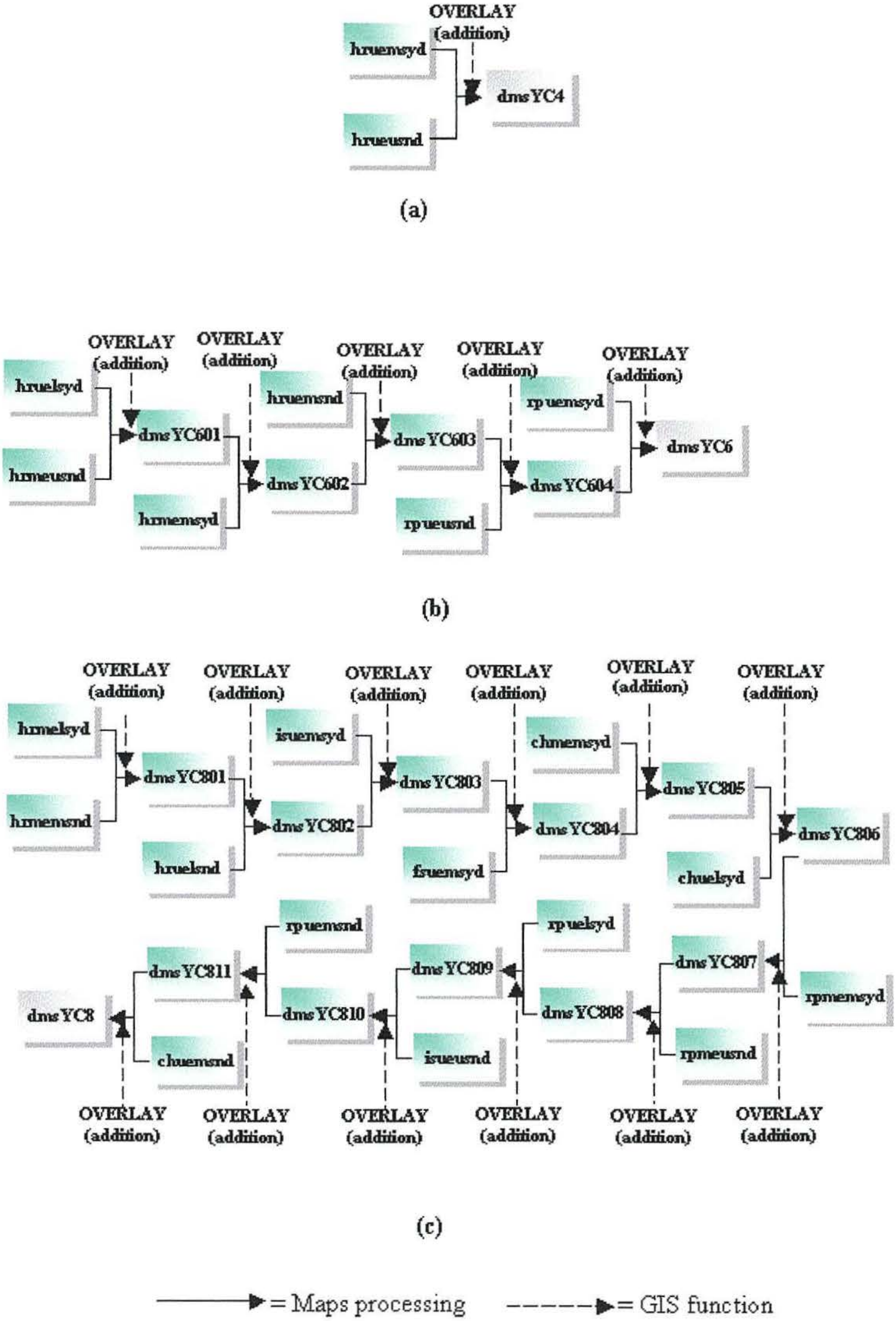
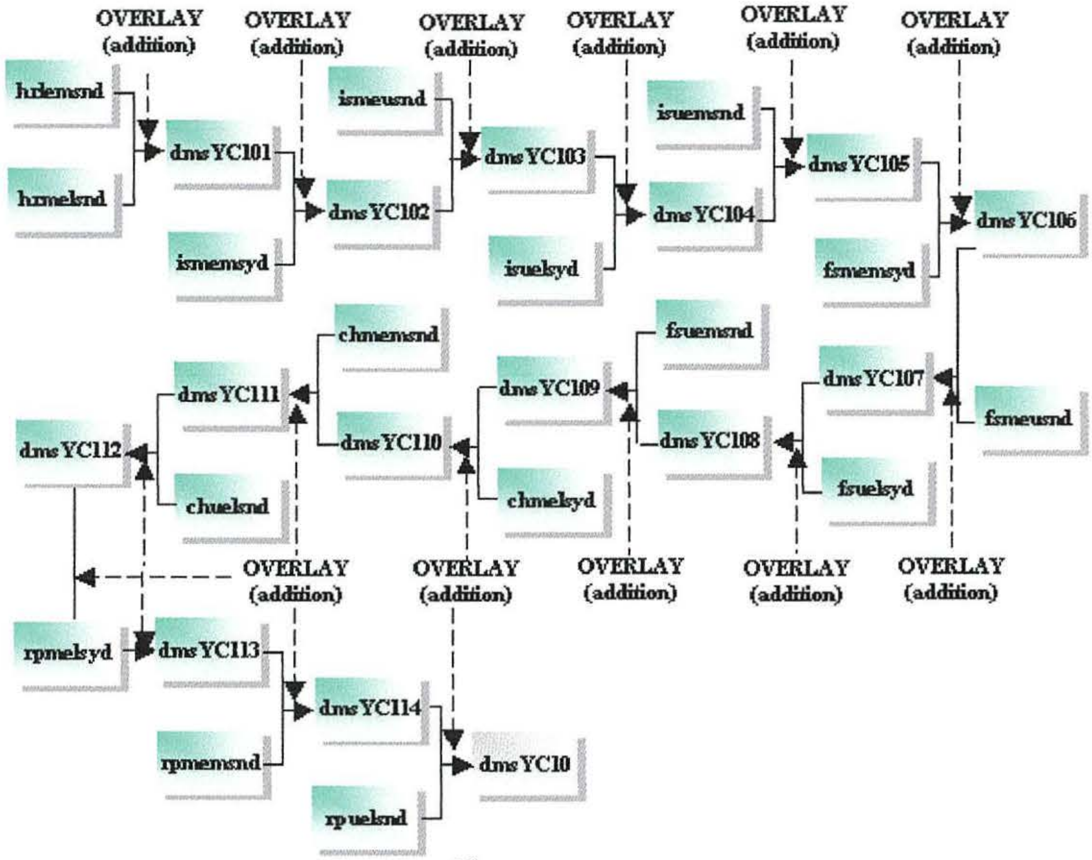
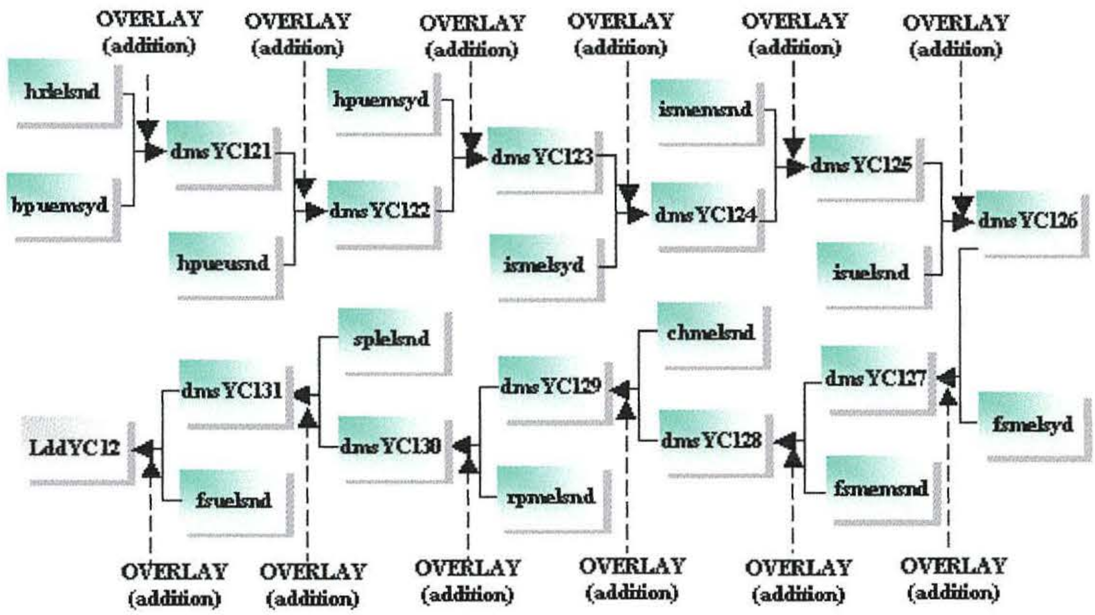


Figure 3.3.1.4 GIS procedures followed in AYC 2 stage (a – l). Sites are grouped with their adjusted yield class.



(d)



(e)

——► = Maps processing - - - - -► = GIS function

Figure 3.3.1.4 (continue) GIS procedures followed in AYC 2 stage (a – l). Sites are grouped with their adjusted yield class.

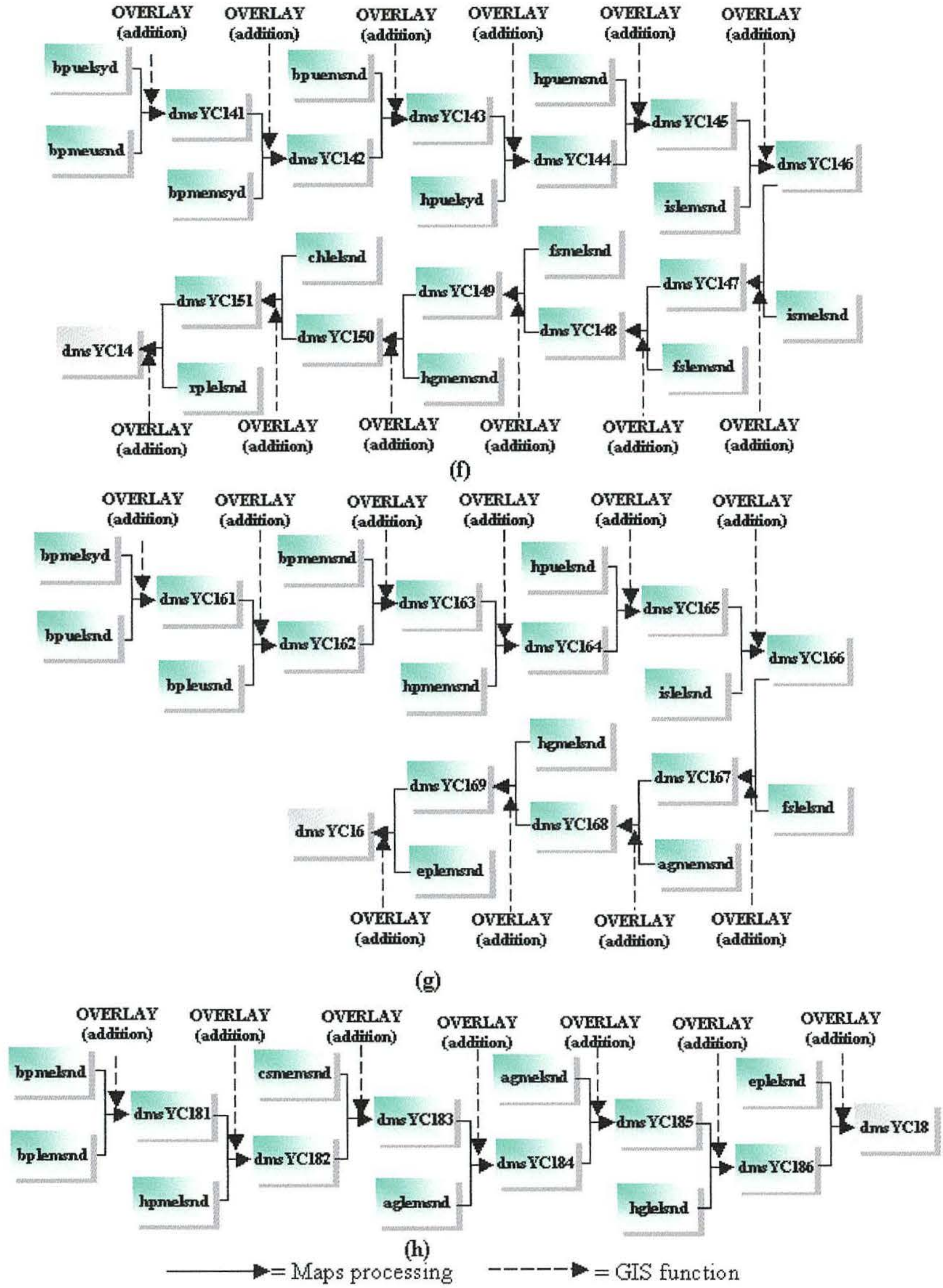


Figure 3.3.1.4 (continue) GIS procedures followed in AYC 2 stage (a – l). Sites are grouped with their adjusted yield class.

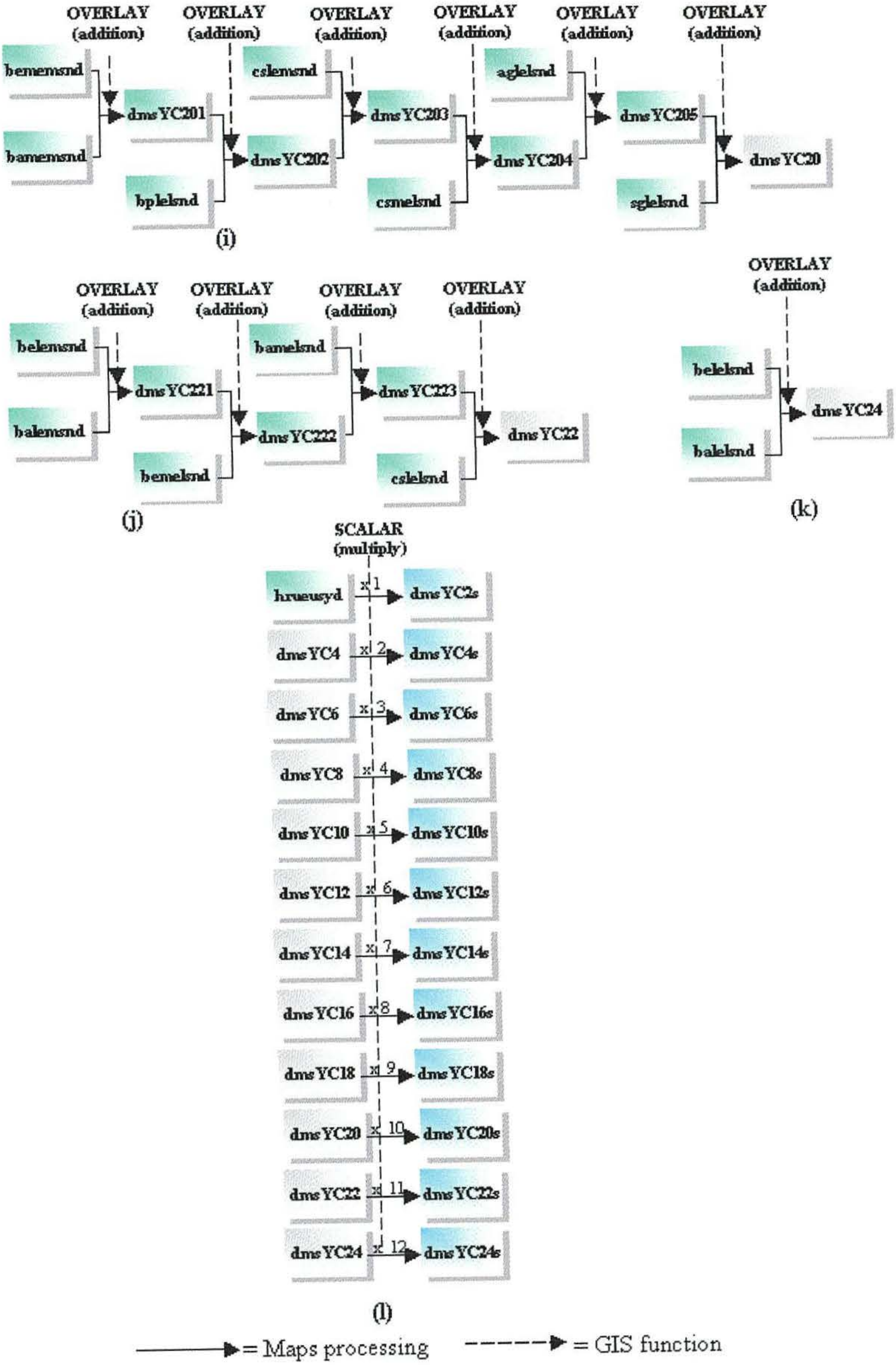


Figure 3.3.1.4 (continue) GIS procedures followed in AYC 2 stage (a – l). Sites are grouped with their adjusted yield class.

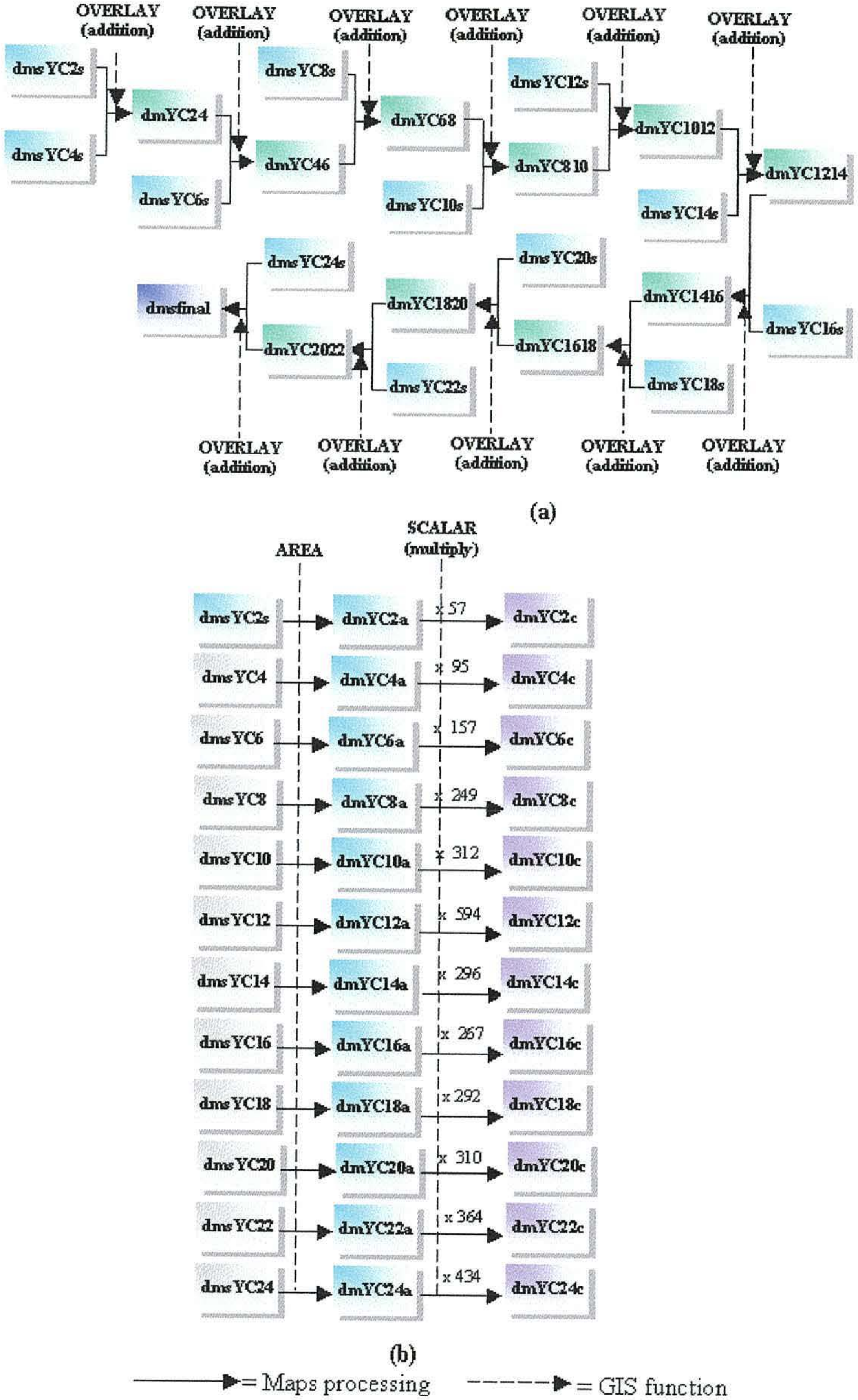


Figure 3.3.1.5 GIS procedures followed in Final stage. Sites are grouped (a) with their adjusted yield class and (b) total organic carbon stock is calculated.

Appendix 3.3.2: Macro routine followed to generate organic carbon model.

3.3.2.1 Input and Process 1

```
convert    x mos90 mos90co  i   3   2   2
resample  x  i mos90co  stsnp90   alamin  plane   m   1  0  245575  300325  299975  379425  1095
resample  x  i snpsoilt   stsnsoil   alamin  plane   m   1  0  245575  300325  299975  379425  1095
resample  x  i snp5con   tsnpalti   alamin  plane   m   1  0  245575  300325  299975  379425  1095
resample  x  i snpslp     tsnpslop  alamin  plane   m   1  0  245575  300325  299975  379425  1095
```

3.3.2.2 Process 2

```
reclass   x  i tsnpalti    alticlss     2  1   0  31  2   31  121    3  121 9999  -9999
reclass   x  i tsnpslop   slopclss     2  1   0   4  2    4     9    3    9 9999  -9999
reclass   x  i windsnp    damsclss     2  0   0   1  1    1  22.0    2 22.0 9999  -9999
reclass   x  i stsnp90    conisnp      2  0   0  16  1   16    17    0   17 9999  -9999
overlay   x 3 alticlss    conisnp      talticl
overlay   x 3 slopclss    conisnp      tslopecl
overlay   x 3 damsclss    conisnp      tdamscl
reclass   x  i stsnsoil   Humcrank     2  0  0   1  1   1    2   0    2   9999  -9999
reclass   x  i stsnsoil   Sandpdzn     2  0  0   2  1   2    3   0    3   9999  -9999
reclass   x  i stsnsoil   Brearth      2  0  0   3  1   3    4   0    4   9999  -9999
reclass   x  i stsnsoil   Brallu       2  0  0   4  1   4    5   0    5   9999  -9999
reclass   x  i stsnsoil   BrPOD        2  0  0   5  1   5    6   0    6   9999  -9999
reclass   x  i stsnsoil   HumBRPD      2  0  0   6  1   6    7   0    7   9999  -9999
reclass   x  i stsnsoil   Ironstag     2  0  0   7  1   7    8   0    8   9999  -9999
reclass   x  i stsnsoil   FerStag      2  0  0   8  1   8    9   0    9   9999  -9999
reclass   x  i stsnsoil   Castgley     2  0  0   9  1   9   10   0   10   9999  -9999
reclass   x  i stsnsoil   CsHugley     2  0  0  10  1  10   11   0   11   9999  -9999
reclass   x  i stsnsoil   Allugley     2  0  0  11  1  11   12   0   12   9999  -9999
reclass   x  i stsnsoil   Sandgley     2  0  0  12  1  12   13   0   13   9999  -9999
reclass   x  i stsnsoil   Humigley     2  0  0  13  1  13   14   0   14   9999  -9999
reclass   x  i stsnsoil   Rawpeat      2  0  0  14  1  14   15   0   15   9999  -9999
reclass   x  i stsnsoil   Earpeat      2  0  0  15  1  15   16   0   16   9999  -9999
```

3.3.2.3. Process 3

overlay	x	3 Humcrank	conisnp	cnHumcra
overlay	x	3 Sandpdzn	conisnp	cnSandpd
overlay	x	3 Brearth	conisnp	cnBrear
overlay	x	3 Brallu	conisnp	cnBrallu
overlay	x	3 BrPOD	conisnp	cnBrPOD
overlay	x	3 HumBRPD	conisnp	cnHumBPD
overlay	x	3 Ironstag	conisnp	cnIronst
overlay	x	3 FerStag	conisnp	cnFerStg
overlay	x	3 Castgley	conisnp	cnCastgl
overlay	x	3 CsHugley	conisnp	cnCsHugl
overlay	x	3 Allugley	conisnp	cnAllugl
overlay	x	3 Sandgley	conisnp	cnSandgl
overlay	x	3 Humigley	conisnp	cnHumigl
overlay	x	3 Rawpeat	conisnp	cnRwpeat
overlay	x	3 Earpeat	conisnp	cnErpeat
overlay	x	3 talticl	cnHumcra	tcHRalti
overlay	x	3 talticl	cnSandpd	tcSPalti
overlay	x	3 talticl	cnBrear	tcBEalti
overlay	x	3 talticl	cnBrallu	tcBAalti
overlay	x	3 talticl	cnBrPOD	tcBPalti
overlay	x	3 talticl	cnHumBPD	tcHBPati
overlay	x	3 talticl	cnIronst	tcISalti
overlay	x	3 talticl	cnFerStg	tcFSalti
overlay	x	3 talticl	cnCastgl	tcCSalti
overlay	x	3 talticl	cnCsHugl	tcCSHati
overlay	x	3 talticl	cnAllugl	tcAGalti
overlay	x	3 talticl	cnSandgl	tcSGalti
overlay	x	3 talticl	cnHumigl	tcHGalti
overlay	x	3 talticl	cnRwpeat	tcRPalti
overlay	x	3 talticl	cnErpeat	tcEPalti

3.3.2.4 Process 4

crosstab	x	tcHRalti	tslopecl	1	tHRalsl
crosstab	x	tcSPalti	tslopecl	1	tSPalsl
crosstab	x	tcBEalti	tslopecl	1	tBEalsl
crosstab	x	tcBAalti	tslopecl	1	tBAalsl
crosstab	x	tcBPalti	tslopecl	1	tBPalsl
crosstab	x	tcHBPati	tslopecl	1	tHBPalsl
crosstab	x	tcISalti	tslopecl	1	tISalsl
crosstab	x	tcFSalti	tslopecl	1	tFSalsl
crosstab	x	tcCSalti	tslopecl	1	tCSalsl

crosstab	x	tcCSHati	tslopecl	1	tCSHalsl
crosstab	x	tcAGalti	tslopecl	1	tAGalsl
crosstab	x	tcSGalti	tslopecl	1	tSGalsl
crosstab	x	tcHGalti	tslopecl	1	tHGalsl
crosstab	x	tcRPalti	tslopecl	1	tRPalsl
crosstab	x	tcEPalti	tslopecl	1	tEPalsl

3.3.2.10 Process 5

reclass x i tHRalsl tHRalre 2 0 0 3 1 3 4 2 4 5 3 5 6 0 6 7 4 7 8 5 8 9 6 9 10 0 10 11 7 11 12 8 12 9999 –9999
reclass x i tSPalsl tSPalre 2 0 0 3 1 3 4 0 4 9999 –9999
reclass x i tBEalsl tBEalre 2 0 0 3 1 3 4 2 4 5 0 5 6 3 6 7 4 7 8 0 8 9999 –9999
reclass x i tBAalsl tBAalre 2 0 0 3 1 3 4 2 4 5 0 5 6 3 6 7 4 7 8 0 8 9999 –9999
reclass x i tBPalsl tBPalre 2 0 0 3 1 3 4 2 4 5 3 5 6 0 6 7 4 7 8 5 8 9 6 9 10 0 10 11 7 11 12 8 12 9999 –9999
reclass x i tHBPalsl tHBPalre 2 0 0 3 1 3 4 2 4 5 0 5 6 3 6 7 4 7 8 0 8 9 5 9 9999 –9999
reclass x i tISalsl tISalre 2 0 0 3 1 3 4 2 4 5 3 5 6 0 6 7 4 7 8 5 8 9 6 9 10 0 10 11 7 11 12 8 12 9999 –9999
reclass x i tFSalsl tFSalre 2 0 0 3 1 3 4 2 4 5 3 5 6 0 6 7 4 7 8 5 8 9 6 9 10 0 10 11 7 11 9999 –9999
reclass x i tCSalsl tCSalre 2 0 0 3 1 3 4 2 4 5 0 5 6 3 6 7 4 7 8 0 8 9999 –9999
reclass x i tCSHalsl tCSHalre 2 0 0 3 1 3 4 2 4 5 3 5 6 0 6 7 4 7 8 5 8 9 0 9 9999 –9999
reclass x i tAGalsl tAGalre 2 0 0 3 1 3 4 2 4 5 0 5 6 3 6 7 4 7 8 0 8 9999 –9999
reclass x i tSGalsl tSGalre 2 0 0 3 1 3 4 0 4 9999 –9999
reclass x i tHGalsl tHGalre 2 0 0 3 1 3 4 2 4 5 0 5 6 3 6 7 0 7 9999 –9999
reclass x i tRPalsl tRPalre 2 0 0 3 1 3 4 2 4 5 3 5 6 0 6 7 4 7 8 5 8 9 0 9 10 6 10 11 7 11 9999 –9999
reclass x i tEPalsl tEPalre 2 0 0 3 1 3 4 0 4 5 2 5 6 0 6 9999 –9999

3.3.2.6 Process 6

crosstab	x	tHRalre	tdamscl	1	tHRald
crosstab	x	tSPalre	tdamscl	1	tSPald
crosstab	x	tBEalre	tdamscl	1	tBEald
crosstab	x	tBAalre	tdamscl	1	tBAald
crosstab	x	tBPalre	tdamscl	1	tBPald
crosstab	x	tHBPalre	tdamscl	1	tHBPald
crosstab	x	tISalre	tdamscl	1	tISald
crosstab	x	tFSalre	tdamscl	1	tFSald
crosstab	x	tCSalre	tdamscl	1	tCSald
crosstab	x	tCSHalre	tdamscl	1	tCSHald
crosstab	x	tAGalre	tdamscl	1	tAGald
crosstab	x	tSGalre	tdamscl	1	tSGald
crosstab	x	tHGalre	tdamscl	1	tHGald
crosstab	x	tRPalre	tdamscl	1	tRPald
crosstab	x	tEPalre	tdamscl	1	tEPald

3.3.2.7 Process 7

```
reclass x i tHRald tHRdsr 3 tHrdsr1
reclass x i tSPald tSPdsr 2 0 0 3 1 3 4 0 4 9999 –9999
reclass x i tBEald tBEdsr 2 0 0 3 1 3 4 2 4 5 3 5 6 4 6 7 0 7 9999 –9999
reclass x i tBAald tBAdsr 2 0 0 3 1 3 4 2 4 5 3 5 6 4 6 7 0 7 8 5 8 9 6 9 9999 –9999
reclass x i tBPald tBPdsr 3 tbpdsr1
reclass x i tHBPald tHBPdsr 3 tHBPdsr1
reclass x i tISald tISdsr 3 tISdsr1
reclass x i tFSald tFSdsr 3 tfsdsr1
reclass x i tCSald tCSdsr 2 0 0 3 1 3 4 2 4 5 3 5 6 4 6 7 0 7 8 5 8 9999 –9999
reclass x i tCSHald tCSHdsr 2 0 0 3 1 3 4 2 4 5 3 5 6 0 6 7 4 7 8 5 8 9 6 9 10 7 10 9999 –9999
reclass x i tAGald tAGdsr 2 0 0 3 1 3 4 2 4 5 3 5 6 4 6 7 0 7 8 5 8 9999 –9999
reclass x i tSGald tSGdsr 2 0 0 3 1 3 4 0 4 9999 –9999
reclass x i tHGald tHGdsr 2 0 0 3 1 3 4 2 4 5 3 5 6 0 6 7 4 7 9999 –9999
reclass x i tRPald tRPdsr 3 tRPdsr1
reclass x i tEPald tEPdsr 2 0 0 3 1 3 4 2 4 5 0 5 9999 –9999
```

3.3.2.8 AYC 1

```
reclass x i tHRdsr hrlelsnd  2 0 0  1 1  1   2   0  2 9999 -9999
reclass x i tHRdsr hrmelsnd  2 0 0  2 1  2   3   0  3 9999 -9999
reclass x i tHRdsr hruelsnd  2 0 0  3 1  3   4   0  4 9999 -9999
reclass x i tHRdsr hrlemsnd  2 0 0  4 1  4   5   0  5 9999 -9999
reclass x i tHRdsr hrmemsnd  2 0 0  5 1  5   6   0  6 9999 -9999
reclass x i tHRdsr hruemsnd  2 0 0  6 1  6   7   0  7 9999 -9999
reclass x i tHRdsr hrmeusnd  2 0 0  7 1  7   8   0  8 9999 -9999
reclass x i tHRdsr hrueusnd  2 0 0  8 1  8   9   0  9 9999 -9999
reclass x i tHRdsr hrmelsyd  2 0 0  9 1  9  10   0 10 9999 -9999
reclass x i tHRdsr hruelsyd  2 0 0 10 1 10  11   0 11 9999 -9999
reclass x i tHRdsr hrmemsyd  2 0 0 11 1 11  12   0 12 9999 -9999
reclass x i tHRdsr hruemsyd  2 0 0 12 1 12  13   0 13 9999 -9999
reclass x i tHRdsr hrueusyd  2 0 0 13 1 13 9999 -9999
reclass x i tSPdsr splelsnd  2 0 0  1 1  1 9999 -9999
reclass x i tBEdsr belelsnd  2 0 0  1 1  1   2   0  2 9999 -9999
reclass x i tBEdsr bemelsnd  2 0 0  2 1  2   3   0  3 9999 -9999
reclass x i tBEdsr belemsnd  2 0 0  3 1  3   4   0  4 9999 -9999
reclass x i tBEdsr bememsnd  2 0 0  4 1  4 9999 -9999
reclass x i tBAdsr balelsnd  2 0 0  1 1  1   2   0  2 9999 -9999
reclass x i tBAdsr bamelsnd  2 0 0  2 1  2   3   0  3 9999 -9999
reclass x i tBAdsr balemsnd  2 0 0  3 1  3   4   0  4 9999 -9999
reclass x i tBAdsr bamemsnd  2 0 0  4 1  4 9999 -9999
reclass x i tBPdsr bplelsnd  2 0 0  1 1  1   2   0  2 9999 -9999
reclass x i tBPdsr bpmelsnd  2 0 0  2 1  2   3   0  3 9999 -9999
reclass x i tBPdsr bpuelsnd  2 0 0  3 1  3   4   0  4 9999 -9999
reclass x i tBPdsr bplemsnd  2 0 0  4 1  4   5   0  5 9999 -9999
```

```
reclass x i tBPdsr bpmemsnd 2 0 0 5 1 5 6 0 6 9999 -9999
reclass x i tBPdsr bpuemsnd 2 0 0 6 1 6 7 0 7 9999 -9999
reclass x i tBPdsr bpleusnd 2 0 0 7 1 7 8 0 8 9999 -9999
reclass x i tBPdsr bpmeusnd 2 0 0 8 1 8 9 0 9 9999 -9999
reclass x i tBPdsr bpmelsyd 2 0 0 9 1 9 10 0 10 9999 -9999
reclass x i tBPdsr bpuelsyd 2 0 0 10 1 10 11 0 11 9999 -9999
reclass x i tBPdsr bpmemsyd 2 0 0 11 1 11 12 0 12 9999 -9999
reclass x i tBPdsr bpuemsyd 2 0 0 12 1 12 9999 -9999
reclass x i tHBPdsr hpmelsnd 2 0 0 1 1 1 2 0 2 9999 -9999
reclass x i tHBPdsr hpuelsnd 2 0 0 2 1 2 3 0 3 9999 -9999
reclass x i tHBPdsr hpmemsnd 2 0 0 3 1 3 4 0 4 9999 -9999
reclass x i tHBPdsr hpuemsnd 2 0 0 4 1 4 5 0 5 9999 -9999
reclass x i tHBPdsr hpueusnd 2 0 0 5 1 5 6 0 6 9999 -9999
reclass x i tHBPdsr hpuelsyd 2 0 0 6 1 6 7 0 7 9999 -9999
reclass x i tHBPdsr hpuemsyd 2 0 0 7 1 7 9999 -9999
reclass x i tISdsr islelsnd 2 0 0 1 1 1 2 0 2 9999 -9999
reclass x i tISdsr ismelsnd 2 0 0 2 1 2 3 0 3 9999 -9999
reclass x i tISdsr isuelsnd 2 0 0 3 1 3 4 0 4 9999 -9999
reclass x i tISdsr islemsnd 2 0 0 4 1 4 5 0 5 9999 -9999
reclass x i tISdsr ismemsnd 2 0 0 5 1 5 6 0 6 9999 -9999
reclass x i tISdsr isuemsnd 2 0 0 6 1 6 7 0 7 9999 -9999
reclass x i tISdsr ismeusnd 2 0 0 7 1 7 8 0 8 9999 -9999
reclass x i tISdsr isueusnd 2 0 0 8 1 8 9 0 9 9999 -9999
reclass x i tISdsr ismelsyd 2 0 0 9 1 9 10 0 10 9999 -9999
reclass x i tISdsr isuelsyd 2 0 0 10 1 10 11 0 11 9999 -9999
reclass x i tISdsr ismemsyd 2 0 0 11 1 11 12 0 12 9999 -9999
reclass x i tISdsr isuemsyd 2 0 0 12 1 12 9999 -9999
reclass x i tFSdsr fslelsnd 2 0 0 1 1 1 2 0 2 9999 -9999
reclass x i tFSdsr fsmelsnd 2 0 0 2 1 2 3 0 3 9999 -9999
reclass x i tFSdsr fsuelsnd 2 0 0 3 1 3 4 0 4 9999 -9999
reclass x i tFSdsr fslemsnd 2 0 0 4 1 4 5 0 5 9999 -9999
reclass x i tFSdsr fsmemsnd 2 0 0 5 1 5 6 0 6 9999 -9999
reclass x i tFSdsr fsuemsnd 2 0 0 6 1 6 7 0 7 9999 -9999
reclass x i tFSdsr fsmeusnd 2 0 0 7 1 7 8 0 8 9999 -9999
reclass x i tFSdsr fsmelsyd 2 0 0 8 1 8 9 0 9 9999 -9999
reclass x i tFSdsr fsuelsyd 2 0 0 9 1 9 10 0 10 9999 -9999
reclass x i tFSdsr fsmemsyd 2 0 0 10 1 10 11 0 11 9999 -9999
reclass x i tFSdsr fsuemsyd 2 0 0 11 1 11 9999 -9999
reclass x i tCSdsr cslelsnd 2 0 0 1 1 1 2 0 2 9999 -9999
reclass x i tCSdsr csmelsnd 2 0 0 2 1 2 3 0 3 9999 -9999
reclass x i tCSdsr cslemsnd 2 0 0 3 1 3 4 0 4 9999 -9999
reclass x i tCSdsr csmemsnd 2 0 0 4 1 4 9999 -9999
reclass x i tCSHdsr chlelsnd 2 0 0 1 1 1 2 0 2 9999 -9999
reclass x i tCSHdsr chmelsnd 2 0 0 2 1 2 3 0 3 9999 -9999
```

```
reclass x i tCSHdsr chuelsnd  2 0 0  3 1  3    4    0  4 9999 -9999
reclass x i tCSHdsr chmemsnd  2 0 0  4 1  4    5    0  5 9999 -9999
reclass x i tCSHdsr chuemsnd  2 0 0  5 1  5    6    0  6 9999 -9999
reclass x i tCSHdsr chmelsyd  2 0 0  6 1  6    7    0  7 9999 -9999
reclass x i tCSHdsr chuelsyd  2 0 0  7 1  7    8    0  8 9999 -9999
reclass x i tCSHdsr chmemsyd  2 0 0  8 1  8 9999 -9999
reclass x i tAGdsr  aglelsnd  2 0 0  1 1  1    2    0  2 9999 -9999
reclass x i tAGdsr  agmelsnd  2 0 0  2 1  2    3    0  3 9999 -9999
reclass x i tAGdsr  aglemsnd  2 0 0  3 1  3    4    0  4 9999 -9999
reclass x i tAGdsr  agmemsnd  2 0 0  4 1  4 9999 -9999
reclass x i tSGdsr  sglelsnd  2 0 0  1 1  1 9999 -9999
reclass x i tHGdsr  hglelsnd  2 0 0  1 1  1    2    0  2 9999 -9999
reclass x i tHGdsr  hgmelsnd  2 0 0  2 1  2    3    0  3 9999 -9999
reclass x i tHGdsr  hgmemsnd  2 0 0  3 1  3 9999 -9999
reclass x i tRPdsr  rplelsnd  2 0 0  1 1  1    2    0  2 9999 -9999
reclass x i tRPdsr  rpmelsnd  2 0 0  2 1  2    3    0  3 9999 -9999
reclass x i tRPdsr  rpuelsnd  2 0 0  3 1  3    4    0  4 9999 -9999
reclass x i tRPdsr  rpmemsnd  2 0 0  4 1  4    5    0  5 9999 -9999
reclass x i tRPdsr  rpuemsnd  2 0 0  5 1  5    6    0  6 9999 -9999
reclass x i tRPdsr  rpmeusnd  2 0 0  6 1  6    7    0  7 9999 -9999
reclass x i tRPdsr  rpueusnd  2 0 0  7 1  7    8    0  8 9999 -9999
reclass x i tRPdsr  rpmelsyd  2 0 0  8 1  8    9    0  9 9999 -9999
reclass x i tRPdsr  rpuelsyd  2 0 0  9 1  9   10    0 10 9999 -9999
reclass x i tRPdsr  rpmemsyd  2 0 0 10 1 10   11    0 11 9999 -9999
reclass x i tRPdsr  rpuemsyd  2 0 0 11 1 11 9999 -9999
reclass x i tEPdsr  eplelsnd  2 0 0  1 1  1    2    0  2 9999 -9999
reclass x i tEPdsr  eplemsnd  2 0 0  2 1  2    3    0  3 9999 -9999
```

3.3.2.9 AYC2

```
overlay x 1 hruemsyd  hrueusnd dmsYC4
overlay x 1 hruelsyd  hrmeusnd dmsYC601
overlay x 1 dmsYC601 hrmemsyd dmsYC602
overlay x 1 dmsYC602 hruemsnd dmsYC603
overlay x 1 dmsYC603 rpueusnd dmsYC604
overlay x 1 dmsYC604 rpuemsyd dmsYC6
overlay x 1 hrmelsyd  hrmemsnd dmsYC801
overlay x 1 dmsYC801 hruelsnd dmsYC802
overlay x 1 dmsYC802 isuemsyd dmsYC803
overlay x 1 dmsYC803 fsuemsyd dmsYC804
overlay x 1 dmsYC804 chmemsyd dmsYC805
overlay x 1 dmsYC805 chuelsyd dmsYC806
overlay x 1 dmsYC806 rpmemsyd dmsYC807
```

```
overlay x 1 dmsYC807 rpmeusnd dmsYC808
overlay x 1 dmsYC808 rpuelsyd dmsYC809
overlay x 1 dmsYC809 isueusnd dmsYC810
overlay x 1 dmsYC810 rpuemsnd dmsYC811
overlay x 1 dmsYC811 chuemsnd dmsYC8
overlay x 1 hrlemsnd hrmelsnd dmsYC101
overlay x 1 dmsYC101 ismemsyd dmsYC102
overlay x 1 dmsYC102 ismeusnd dmsYC103
overlay x 1 dmsYC103 isuelsyd dmsYC104
overlay x 1 dmsYC104 isuemsnd dmsYC105
overlay x 1 dmsYC105 fsmemsyd dmsYC106
overlay x 1 dmsYC106 fsmeusnd dmsYC107
overlay x 1 dmsYC107 fsuelsyd dmsYC108
overlay x 1 dmsYC108 fsuemsnd dmsYC109
overlay x 1 dmsYC109 chmelsyd dmsYC110
overlay x 1 dmsYC110 chmemsnd dmsYC111
overlay x 1 dmsYC111 chuelsnd dmsYC112
overlay x 1 dmsYC112 rpmelsyd dmsYC113
overlay x 1 dmsYC113 rpmemsnd dmsYC114
overlay x 1 dmsYC114 rpuelsnd dmsYC10
overlay x 1 hrlelsnd bpuemsyd dmsYC121
overlay x 1 dmsYC121 hpueusnd dmsYC122
overlay x 1 dmsYC122 hpuemsyd dmsYC123
overlay x 1 dmsYC123 ismelsyd dmsYC124
overlay x 1 dmsYC124 ismemsnd dmsYC125
overlay x 1 dmsYC125 isuelsnd dmsYC126
overlay x 1 dmsYC126 fsmelsyd dmsYC127
overlay x 1 dmsYC127 fsmemsnd dmsYC128
overlay x 1 dmsYC128 chmelsnd dmsYC129
overlay x 1 dmsYC129 rpmelsnd dmsYC130
overlay x 1 dmsYC130 splelsnd dmsYC131
overlay x 1 dmsYC131 fsuelsnd dmsYC12
overlay x 1 bpuelsyd bpmeusnd dmsYC141
overlay x 1 dmsYC141 bpmemsyd dmsYC142
overlay x 1 dmsYC142 bpuemsnd dmsYC143
overlay x 1 dmsYC143 hpuelsyd dmsYC144
overlay x 1 dmsYC144 hpuemsnd dmsYC145
overlay x 1 dmsYC145 islemsnd dmsYC146
overlay x 1 dmsYC146 ismelsnd dmsYC147
overlay x 1 dmsYC147 fslemsnd dmsYC148
overlay x 1 dmsYC148 fsmelsnd dmsYC149
overlay x 1 dmsYC149 hgmemsnd dmsYC150
overlay x 1 dmsYC150 chlelsnd dmsYC151
overlay x 1 dmsYC151 rplelsnd dmsYC14
```

```
overlay x 1 bpmelsyd bpuelsnd dmsYC161
overlay x 1 dmsYC161 bpleusnd dmsYC162
overlay x 1 dmsYC162 bpmemsnd dmsYC163
overlay x 1 dmsYC163 hpmemsnd dmsYC164
overlay x 1 dmsYC164 hpuelsnd dmsYC165
overlay x 1 dmsYC165 islelsnd dmsYC166
overlay x 1 dmsYC166 fslelsnd dmsYC167
overlay x 1 dmsYC167 agmemsnd dmsYC168
overlay x 1 dmsYC168 hgmelsnd dmsYC169
overlay x 1 dmsYC169 eplemsnd dmsYC16
overlay x 1 bplemsnd bpmelsnd dmsYC181
overlay x 1 dmsYC181 hpmelsnd dmsYC182
overlay x 1 dmsYC182 csmemsnd dmsYC183
overlay x 1 dmsYC183 aglemsnd dmsYC184
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overlay x 1 dmsYC185 hglelsnd dmsYC186
overlay x 1 dmsYC186 eplelsnd dmsYC18
overlay x 1 bememsnd bamemsnd dmsYC201
overlay x 1 dmsYC201 bplelsnd dmsYC202
overlay x 1 dmsYC202 cslemsnd dmsYC203
overlay x 1 dmsYC203 csmelsnd dmsYC204
overlay x 1 dmsYC204 aglelsnd dmsYC205
overlay x 1 dmsYC205 sglelsnd dmsYC20
overlay x 1 belemsnd balemsnd dmsYC221
overlay x 1 dmsYC221 bemelsnd dmsYC222
overlay x 1 dmsYC222 bamelsnd dmsYC223
overlay x 1 dmsYC223 cslelsnd dmsYC22
overlay x 1 belelsnd balelsnd dmsYC24
scalar x hrueusyd dmsYC2s 3 1
scalar x dmsYC4 dmsYC4s 3 2
scalar x dmsYC6 dmsYC6s 3 3
scalar x dmsYC8 dmsYC8s 3 4
scalar x dmsYc10 dmsYc10s 3 5
scalar x dmsYc12 dmsYc12s 3 6
scalar x dmsYc14 dmsYc14s 3 7
scalar x dmsYc16 dmsYc16s 3 8
scalar x dmsYc18 dmsYc18s 3 9
scalar x dmsYc20 dmsYc20s 3 10
scalar x dmsYc22 dmsYc22s 3 11
scalar x dmsYc24 dmsYc24s 3 12
```

3.3.2.10 Final

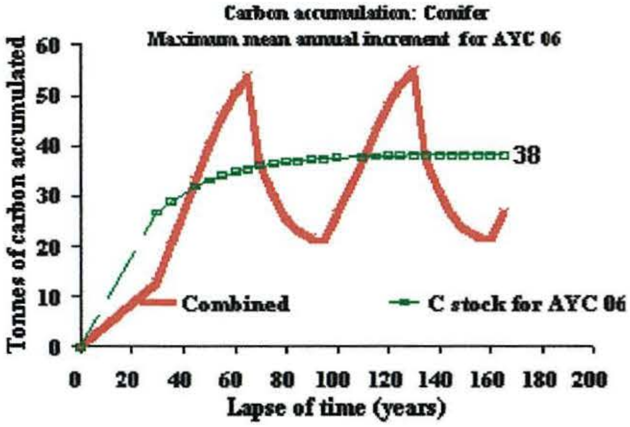
```
overlay x 1 dmsYC2s dmsYC4s dmYc24
overlay x 1 dmYc24 dmsYC6s dmYc46
overlay x 1 dmYc46 dmsYC8s dmYc68
overlay x 1 dmYc68 dmsYc10s dmYc810
overlay x 1 dmYc810 dmsYc12s dmYc1012
overlay x 1 dmYc1012 dmsYc14s dmYc1214
overlay x 1 dmYc1214 dmsYc16s dmYc1416
overlay x 1 dmYc1416 dmsYc18s dmyc1618
overlay x 1 dmyc1618 dmsYc20s dmYc1820
overlay x 1 dmYc1820 dmsYc22s dmyc2022
overlay x 1 dmYc2022 dmsYc24s dmsfinal
area x dmsYC2s 1 2 dmYC2a
area x dmsYC4 1 2 dmYC4a
area x dmsYC6 1 2 dmYC6a
area x dmsYC8 1 2 dmYC8a
area x dmsYc10 1 2 dmYc10a
area x dmsYc12 1 2 dmYc12a
area x dmsYc14 1 2 dmYc14a
area x dmsYc16 1 2 dmYc16a
area x dmsYc18 1 2 dmYc18a
area x dmsYc20 1 2 dmYc20a
area x dmsYc22 1 2 dmYc22a
area x dmsYc24 1 2 dmYc24a
scalar x dmYC2a dmYC2c 3 57
scalar x dmYC4a dmYC4c 3 95
scalar x dmYC6a dmYC6c 3 157
scalar x dmYC8a dmYC8c 3 249
scalar x dmYc10a dmYc10c 3 312
scalar x dmYc12a dmYc12c 3 594
scalar x dmYc14a dmYc14c 3 296
scalar x dmYc16a dmYc16c 3 267
scalar x dmYc18a dmYc18c 3 292
scalar x dmYc20a dmYc20c 3 310
scalar x dmYc22a dmYc22c 3 364
scalar x dmYc24a dmYc24c 3 434
```

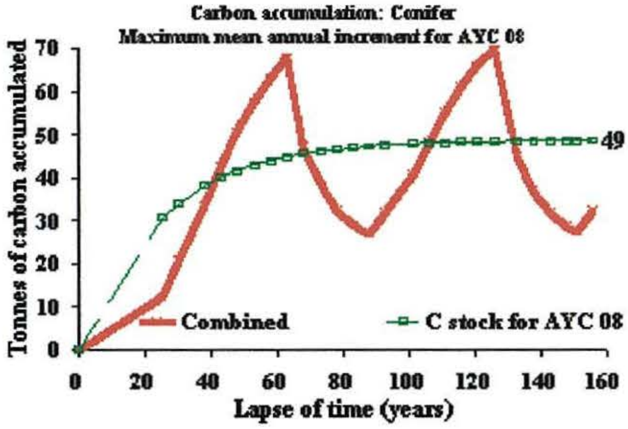
3.3.2.11 Replacing scenarios

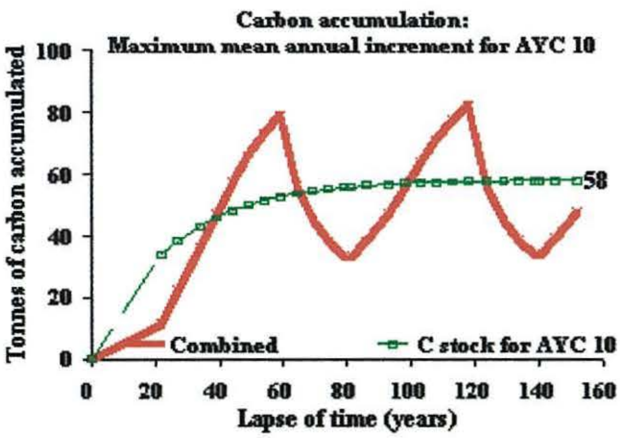
```
reclass x i dmsfinal scnario1 2 0 0 1 1 1 4 0 4 9999 -9999
reclass x i dmsfinal scnario2 2 0 0 4 1 4 7 0 7 9999 -9999
reclass x i dmsfinal scnario3 2 0 0 7 1 7 9 0 9 9999 -9999
reclass x i dmsfinal Natwood1 2 0 0 1 1 1 4 2 4 7 3 7 9 0 9 9999 -9999
```

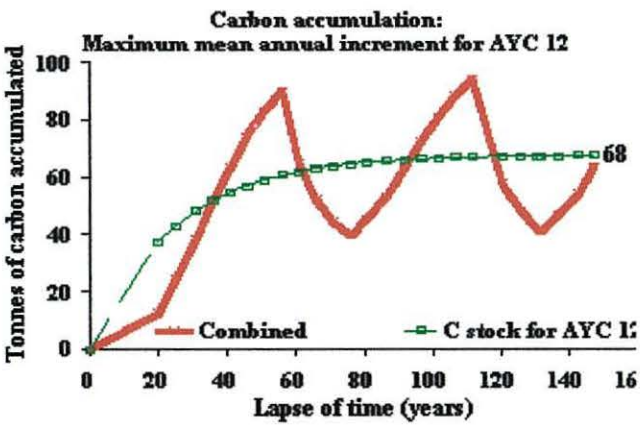
<u>Appendix 3.3.3</u>

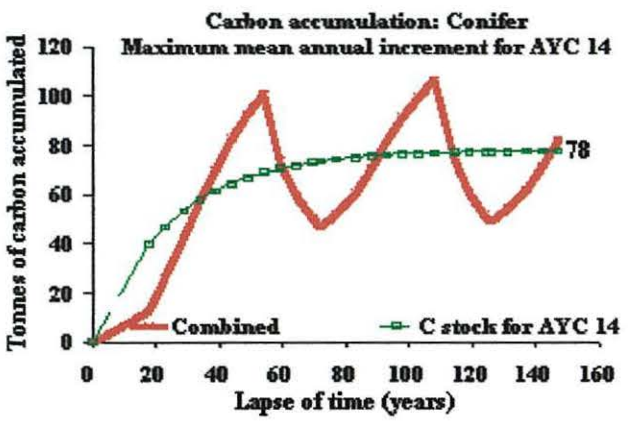
Carbon stock (maximum mean annual increment period) of *Picea sitchensis* (conifer) and *Quercus* species (broadleaved) according to adjusted yield class (AYC).

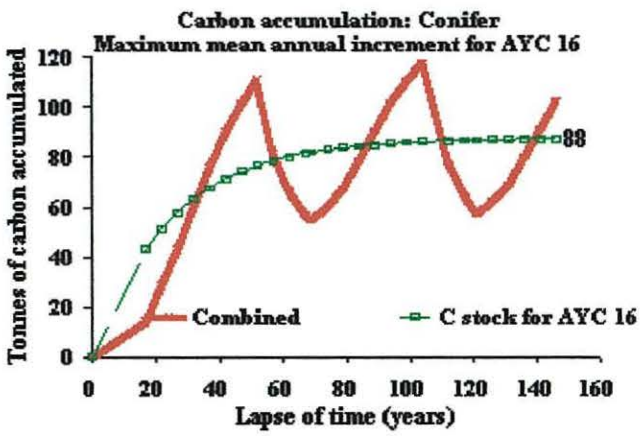


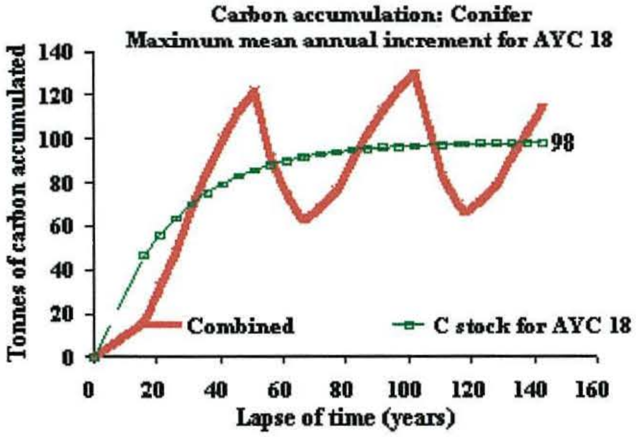


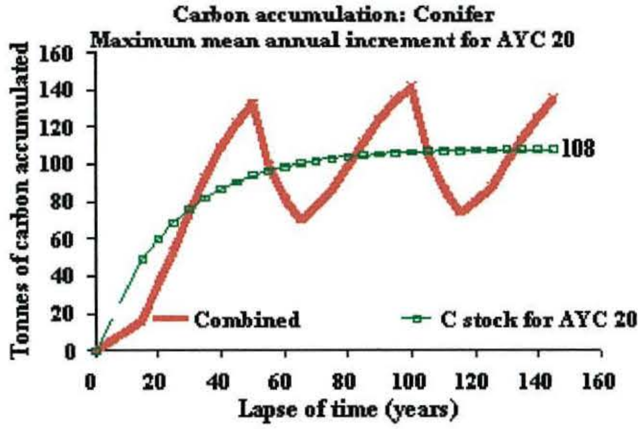


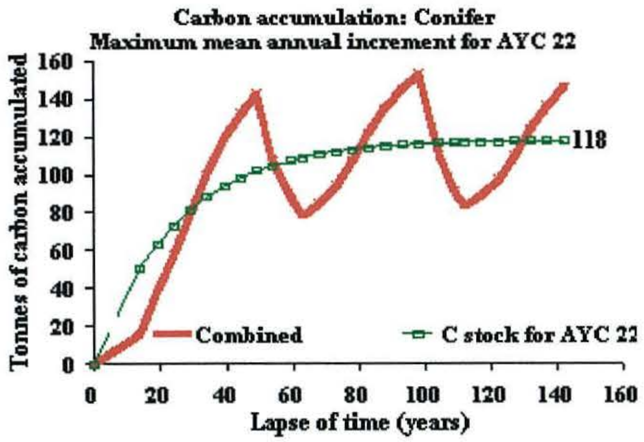


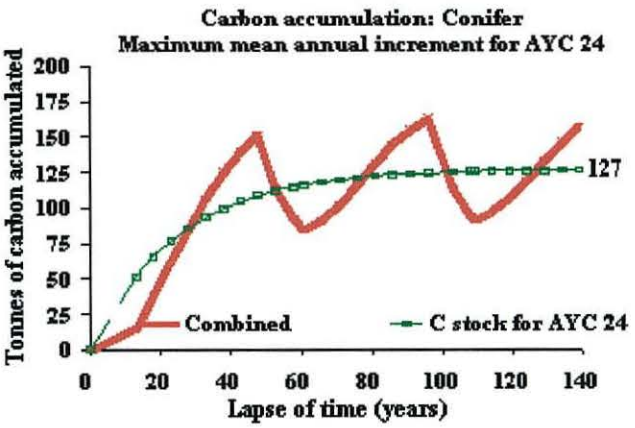


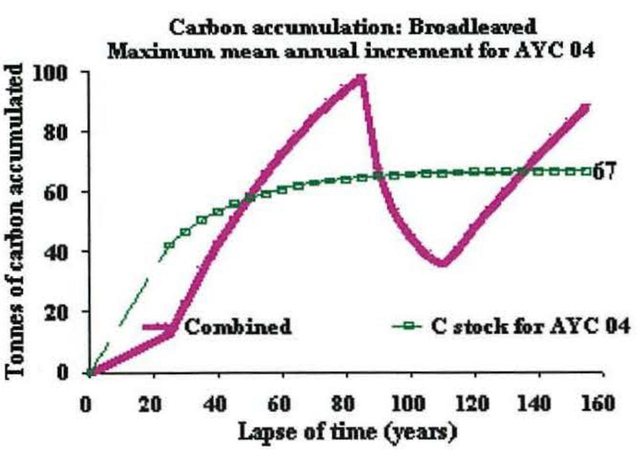


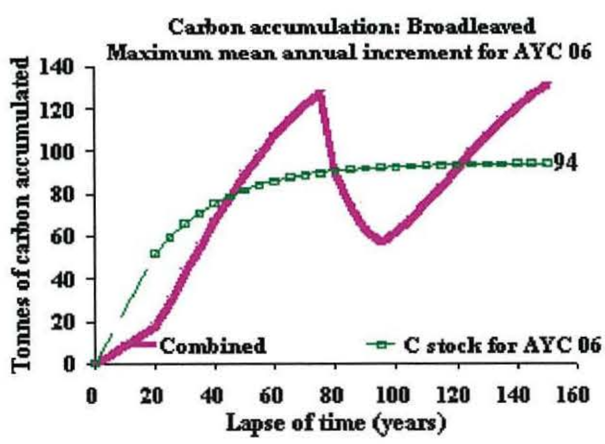

Carbon accumulation: Conifer
Maximum mean annual increment for AYC 18
Tonnes of carbon accumulated
Lapse of time (years)
Combined
C stock for AYC 18
98


Carbon accumulation: Conifer
Maximum mean annual increment for AYC 20
Tonnes of carbon accumulated
Lapse of time (years)
Combined
C stock for AYC 20
108


Carbon accumulation: Conifer
Maximum mean annual increment for AYC 22
Tonnes of carbon accumulated
Lapse of time (years)
Combined
118


Carbon accumulation: Conifer
Maximum mean annual increment for AYC 24
Tonnes of carbon accumulated
Lapse of time (years)
Combined
C stock for AYC 24
127


Carbon accumulation: Broadleaved
Maximum mean annual increment for AYC 04
Tonnes of carbon accumulated
Lapse of time (years)
Combined
C stock for AYC 04
67


Carbon accumulation: Broadleaved
Maximum mean annual increment for AYC 06
Tonnes of carbon accumulated
Lapse of time (years)
Combined
C stock for AYC 06
94

Appendix 3.3.4

Classification of soils of the Snowdonia National Park (Avery, 1980).

Major soil group	Soil group	Soil sub group
Lithomorphic soils: Soils with a distinct humose or peaty topsoil and no diagnostic subsurface horizon, i.e. normally with bed rock or little altered unconsolidated material within 30 cm.	**a) Rankers**: Non calcareous, over non calcareous, non-alluvial substratum (excluding sands) or hard limestone. **b) Sand–pararendzinas** In calcareous, non-alluvial sandy material	***a.1) Humic Ranker*** ***b.1) Typical sand–pararendzinas***
Brown soils: Mineral soils with a weathered or argillic B horizon and no gley sub-surface horizon within 40 cm depth.	**a) Brown Earth** (*sensu stricto*): Non alluvial, loamy or clayey, with a weathered B horizon in non-calcareous material. **b) Brown alluvial soils**: With a weathered B horizon in non-calcareous loamy or clayey recent alluvium.	***a.1) Typical brown earth.*** ***b.1) Typical brown alluvial soils***
Podzolic soils: Mineral soils with a podzolic B horizon (Bs, Bh and /or thin ironpan)	**a) Brown podzolic soils**: With a Bs horizon only and no albic E or gleyed subsurface horizon **b) Stagnopodzols**: With a peaty top soil and / or gleyed albic E over a thin iron pan or Bs horizon	***a.1) Typical brown podzolic soils*** ***a.2) Humic brown podzolic soils*** ***b.1) Ironpan stagnopodzols*** ***b.2) Ferric stagnopodzols***
Surface-water gley soils: Non-alluvial, non-podzolic soils with a non-calcareous gleyed	**a) Stagnogley soils**: With a distinct top soils. **b)Stagnohumic gley soils**: With a humose or peaty top soil	***a.1) Cambic stagnogley soils*** ***b.1) Cambic stagnohumic gley soils***
Ground water gley soils: Non-podzolic soils with a distinct, humose or peaty topsoil and a gleyed subsurface horizon within 40 cm depth.	**a) Alluvial gley soils**: With a distinct top soil, in loamy or clayey recent alluvium **b) Humic gley soils**: Non-alluvial, oamy or clayey, with a humose or peaty topsoil	***a.1) Typical alluvial gley soils*** ***a.2) Typical sandy gley soils*** ***b.1) Typical humic gley soils***
Peat (organic) soils: Soils having more than 40 cm of organic material within the upper 80 cm, or more than 30 cm of organic material resting on bedrock or extremely stony material.	**a) Raw peat soils:** Without any earthy top soil or ripened mineral surface layer. **b) Earthy peat soils**: With an earthy top soil or ripened mineral surface layer	***a.1) Raw oligo-amorphous peat soils*** ***b.1) Earthy eutro-amorphous peat soils***

Avery, B.W. 1980. Systems of soil classification for England and Wales (higher categories). *Soil survey Technical Monograph No. 14*. Harpenden. UK

Soil Survey of England and Wales. 1983. *Legend for the 1:250,000 soil map of England and Wales*. Rothamsted Experimental Station, Harpenden. UK. 21pp.

Appendix 3.4.1: Organic carbon stock in different soil layers in the study area

Soil class	Soil class abbreviation	Soil organic carbon (tonne/ hectare)			
		O layer	A layer	B layer	C layer
Humic Ranker	**HR**	5.67	20.79	144	-
Sand-parendzinas	**SP**	3.51	4.89	0.48	2.1
Brown earth	**BE**	18	30.8	39.48	97.44
Brown alluvial	**BA**	18	30.8	32.76	33.6
Brown Podzolic	**BP**	7.56	27.72	40.32	42.6
Humic Brown Podzolic	**HBP**	8.25	95.64	59.52	18
Ironpan stagnopodzols	**IS**	-	21	35.76	36.21
Ferric stagnopodzols	**FS**	-	-	120.47	71.58
Cambic stagno gley	**CS**	4.65	17.05	20.55	77.04
Cambic stagnohumic gley	**CSH**	6.3	23.1	18.06	82.47
Alluvial gley	**AG**	7.59	27.83	41.88	107.76
Sandy gley	**SG**	5.88	97.44	31.36	30.45
Humic gley	**HG**	17.64	64.68	94.08	31.41
Raw oligo amorphous peat	**RP**	-	44.4	183.6	972
Earthy eutro-amorphous peat	**EP**	-	44.4	183.6	972

Appendix 3.4.2

Estimating the soil type organic carbon for the SNP. Here, B. density means bulk density of soil;

Soil class- Humic Ranker for SNP

**Carbon present in layers (Rudeforth *et al*, 1984);
Bulk density: Expert advice and Rudeforth *et al*, 1984.

Initial depth cm	Final depth cm	Org. C %	Org. C gm/gm	B. density gm/cm^3	Org. C gm/cm^3	Org. C gm / m^2 /horizon	Org. C tonne / ha /horizon
0	3	6.3	0.063	0.3	0.0189	567	5.67
3	14	6.3	0.063	0.3	0.0189	2079	20.79
14	30	30	0.3	0.3	0.09	14400	144
	Total					**17046**	**170.46**

Soil class- Sand- parendzinas for SNP

**Carbon present in layers (Rudeforth *et al*, 1984);
Bulk density: Expert advice and Rudeforth *et al*, 1984.

Initial depth cm	Final depth cm	Org. C %	Org. C gm/gm	B. density gm/cm^3	Org. C gm/cm^3	Org. C gm / m^2 /horizon	Org. C tonne / ha /horizon
0	3	3.9	0.039	0.3	0.0117	351	3.51
3	7	3.9	0.039	0.3	0.0117	468	4.68
7	14	0.1	0.001	0.3	0.0003	21	0.21
14	30	0.1	0.001	0.3	0.0003	48	0.48
30	100	0.1	0.001	0.3	0.0003	210	2.1
	Total					**1098**	**10.98**

Soil class- Brown earth for SNP

**Carbon present in layers (Rudeforth *et al*, 1984);
Bulk density: Expert advice and Rudeforth *et al*, 1984.

Initial depth cm	Final depth cm	Org. C %	Org. C gm/gm	B. density gm/cm^3	Org. C gm/cm^3	Org. C gm / m^2 /horizon	Org. C tonne / ha /horizon
0	3	24	0.24	0.25	0.06	1800	18
3	14	3.5	0.035	0.8	0.028	3080	30.8
14	23	3.5	0.035	0.8	0.028	2520	25.2
23	30	1.7	0.017	1.2	0.0204	1428	14.28
30	46	1.7	0.017	1.2	0.0204	3264	32.64
46	100	1	0.01	1.2	0.012	6480	64.8
	Total					**18572**	**185.72**

Soil class- Brown alluvial for SNP

**Carbon present in layers (Rudeforth *et al*, 1984);
Bulk density: Expert advice and Rudeforth *et al*, 1984.

Initial depth cm	Final depth cm	Org. C %	Org. C gm/gm	B. density gm/cm^3	Org. C gm/cm^3	Org. C gm / m^2 /horizon	Org. C tonne / ha /horizon
0	3	24	0.24	0.25	0.06	1800	18
3	14	3.5	0.035	0.8	0.028	3080	30.8
14	23	3.5	0.035	0.8	0.028	2520	25.2
23	30	0.9	0.009	1.2	0.0108	756	7.56
30	100	0.4	0.004	1.2	0.0048	3360	33.6
	Total					**11516**	**115.16**

Soil class- Brown Podzolic for SNP

**Carbon present in layers (Rudeforth *et al*, 1984);
Bulk density: Expert advice and Rudeforth *et al*, 1984.

Initial depth cm	Final depth cm	Org. C %	Org. C gm/gm	B. density gm/cm^3	Org. C gm/cm^3	Org. C gm / m^2 /horizon	Org. C tonne / ha /horizon
0	3	2.1	0.021	1.2	0.0252	756	7.56
3	14	2.1	0.021	1.2	0.0252	2772	27.72
14	30	2.1	0.021	1.2	0.0252	4032	40.32
30	55	0.7	0.007	1.2	0.0084	2100	21
55	100	0.4	0.004	1.2	0.0048	2160	21.6
	Total					**11820**	**118.2**

Soil class- Humic Brown Podzolic for SNP

**Carbon present in layers (Rudeforth *et al*, 1984);
Bulk density: Expert advice and Rudeforth *et al*, 1984.

Initial depth cm	Final depth cm	Org. C %	Org. C gm/gm	B. density gm/cm^3	Org. C gm/cm^3	Org. C gm / m^2 /horizon	Org. C tonne / ha /horizon
0	3	11	0.11	0.25	0.0275	825	8.25
3	7	11	0.11	1.2	0.132	5280	52.8
7	14	5.1	0.051	1.2	0.0612	4284	42.84
14	20	5.1	0.051	1.2	0.0612	3672	36.72
20	30	1.9	0.019	1.2	0.0228	2280	22.8
30	44	0.6	0.006	1.2	0.0072	1008	10.08
44	100	0.6	0.006	1.2	0.0072	4032	40.32
	Total					**21381**	**213.81**

Soil class- Ironpan stagnopodzols for SNP

**Carbon present in layers (Rudeforth *et al*, 1984);
Bulk density: Expert advice and Rudeforth *et al*, 1984.

Initial depth cm	Final depth cm	Org. C %	Org. C gm/gm	B. density gm/cm^3	Org. C gm/cm^3	Org. C gm / m^2 /horizon	Org. C tonne / ha /horizon
8	14	14	0.14	0.25	0.035	2100	21
14	18	14	0.14	0.25	0.035	1400	14
18	22	2.6	0.026	0.8	0.0208	832	8.32
22	30	1.4	0.014	1.2	0.0168	1344	13.44
30	54	0.4	0.004	1.25	0.005	1200	12
54	66	0.6	0.006	1.45	0.0087	1044	10.44
66	100	0.3	0.003	1.35	0.0041	1377	13.77
	Total					**9297**	**92.97**

Soil class- Ferric stagnopodzols for SNP

**Carbon present in layers (Rudeforth *et al*, 1984);
Bulk density: Expert advice and Rudeforth *et al*, 1984.

Initial depth cm	Final depth cm	Org. C %	Org. C gm/gm	B. density gm/cm^3	Org. C gm/cm^3	Org. C gm / m^2 /horizon	Org. C tonne / ha /horizon
15	28	35	0.35	0.25	0.0875	11375	113.75
28	30	2.8	0.028	1.2	0.0336	672	6.72
30	36	2.8	0.028	1.2	0.0336	2016	20.16
36	45	2.1	0.021	0.8	0.0168	1512	15.12
45	75	0.7	0.007	1.3	0.0091	2730	27.3
75	100	0.3	0.003	1.2	0.0036	900	9
	Total					**19205**	**192.05**

Soil class- Cambic stagno gley for SNP

**Carbon present in layers (Rudeforth *et al*, 1984);
Bulk density: Expert advice and Rudeforth *et al*, 1984.

Initial depth cm	Final depth cm	Org. C %	Org. C gm/gm	B. density gm/cm^3	Org. C gm/cm^3	Org. C gm / m^2 /horizon	Org. C tonne / ha /horizon
0	3	1	0.01	1.55	0.0155	465	4.65
3	14	1	0.01	1.55	0.0155	1705	17.05
14	25	1	0.01	1.55	0.0155	1705	17.05
25	30	0.5	0.005	1.4	0.007	350	3.5
30	47	0.5	0.005	1.4	0.007	1190	11.9
47	60	0.4	0.004	1.45	0.0058	754	7.54
60	100	0.9	0.009	1.6	0.0144	5760	57.6
	Total					**11929**	**119.29**

Soil class- Cambic stagnohumic gley for SNP

**Carbon present in layers (Rudeforth *et al*, 1984);
Bulk density: Expert advice and Rudeforth *et al*, 1984.

Initial depth cm	Final depth cm	Org. C %	Org. C gm/gm	B. density gm/cm^3	Org. C gm/cm^3	Org. C gm / m^2 /horizon	Org. C tonne / ha /horizon
0	3	7	0.07	0.3	0.021	630	6.3
3	14	7	0.07	0.3	0.021	2310	23.1
14	18	7	0.07	0.3	0.021	840	8.4
18	30	0.7	0.007	1.15	0.0081	966	9.66
30	48	0.7	0.007	1.15	0.0081	1449	14.49
48	78	1.1	0.011	1.1	0.0121	3630	36.3
78	100	0.9	0.009	1.6	0.0144	3168	31.68
	Total					**12993**	**129.93**

Soil class- Alluvial gley for SNP

**Carbon present in layers (Rudeforth *et al*, 1984);
Bulk density: Expert advice and Rudeforth *et al*, 1984.

Initial depth cm	Final depth cm	Org. C %	Org. C gm/gm	B. density gm/cm^3	Org. C gm/cm^3	Org. C gm / m^2 /horizon	Org. C tonne / ha /horizon
0	3	2.2	0.022	1.15	0.0253	759	7.59
3	14	2.2	0.022	1.15	0.0253	2783	27.83
14	26	2.2	0.022	1.15	0.0253	3036	30.36
26	30	2.4	0.024	1.2	0.0288	1152	11.52
30	38	2.4	0.024	1.2	0.0288	2304	23.04
38	64	1.1	0.011	1.2	0.0132	3432	34.32
64	100	1	0.01	1.4	0.014	5040	50.4
	Total					**18506**	**185.06**

Soil class- Sandy gley for SNP

**Carbon present in layers (Rudeforth *et al*, 1984);
Bulk density: Expert advice and Rudeforth *et al*, 1984.

Initial depth cm	Final depth cm	Org. C %	Org. C gm/gm	B. density gm/cm^3	Org. C gm/cm^3	Org. C gm / m^2 /horizon	Org. C tonne / ha /horizon
0	3	1.4	0.014	1.4	0.0196	588	5.88
3	14	1.4	0.014	1.4	0.0196	2156	21.56
14	30	1.4	0.014	1.4	0.0196	3136	31.36
30	45	0.5	0.005	1.45	0.0073	1087.5	10.875
45	70	0.3	0.003	1.45	0.0044	1087.5	10.875
70	100	0.2	0.002	1.45	0.0029	870	8.7
	Total					**8925**	**89.25**

Soil class- Humic gley for SNP

**Carbon present in layers (Rudeforth *et al*, 1984);
Bulk density: Expert advice and Rudeforth *et al*, 1984.

Initial depth cm	Final depth cm	Org. C %	Org. C gm/gm	B. density gm/cm^3	Org. C gm/cm^3	Org. C gm / m^2 /horizon	Org. C tonne / ha /horizon
0	3	5.6	0.056	1.05	0.0588	1764	17.64
3	14	5.6	0.056	1.05	0.0588	6468	64.68
14	30	5.6	0.056	1.05	0.0588	9408	94.08
30	41	0.7	0.007	1.5	0.0105	1155	11.55
41	52	0.3	0.003	1.8	0.0054	594	5.94
52	100	0.2	0.002	1.45	0.0029	1392	13.92
	Total					**20781**	**207.81**

Soil class- Raw oligo amorphous peat for SNP

**Carbon present in layers (Rudeforth *et al*, 1984);
Bulk density: Expert advice and Rudeforth *et al*, 1984.

Initial depth cm	Final depth cm	Org. C %	Org. C gm/gm	B. density gm/cm^3	Org. C gm/cm^3	Org. C gm / m^2 /horizon	Org. C tonne / ha /horizon
10	14	37	0.37	0.3	0.111	4440	44.4
14	20	37	0.37	0.3	0.111	6660	66.6
20	30	39	0.39	0.3	0.117	11700	117
30	45	39	0.39	0.3	0.117	17550	175.5
45	70	39	0.39	0.3	0.117	29250	292.5
70	100	56	0.56	0.3	0.168	50400	504
	Total					**120000**	**1200**

Soil class- Earthy eutro-amorphous peat for SNP

**Carbon present in layers (Rudeforth *et al*, 1984);
Bulk density: Expert advice and Rudeforth *et al*, 1984.

Initial depth cm	Final depth cm	Org. C %	Org. C gm/gm	B. density gm/cm^3	Org. C gm/cm^3	Org. C gm / m^2 /horizon	Org. C tonne / ha /horizon
10	14	37	0.37	0.3	0.111	4440	44.4
14	20	37	0.37	0.3	0.111	6660	66.6
20	30	39	0.39	0.3	0.117	11700	117
30	45	39	0.39	0.3	0.117	17550	175.5
45	70	39	0.39	0.3	0.117	29250	292.5
70	100	56	0.56	0.3	0.168	50400	504
	Total					**120000**	**1200**

Appendix 3.4.3: Soil carbon stock for the conifer plantations of the SNP.

Patch name	Area (ha)	AYC	Soil type carbon stock (tonne)	Tree and litter carbon stock (tonne / hectare)	TLO_{CS} / MOC_{TL}*	Soil organic carbon stock (tonnes)
a	b	c	d	e (TLO_{CS})	f = e / 91.42	g = b x d x f
Humic Ranker						
hrlelsnd	0.25	12	170.46	87	0.95	41
hrlemsnd	1	10	170.46	75	0.82	140
hrmelsnd	1215.5	10	170.46	75	0.82	169986
hrmelsyd	3.5	8	170.46	63	0.69	411
hrmemsnd	350.5	8	170.46	63	0.69	41174
hrmemsyd	2.5	6	170.46	49	0.54	228
hrmeusnd	17.25	6	170.46	49	0.54	1576
hruelsnd	8	8	170.46	63	0.69	940
hruelsyd	5	6	170.46	49	0.54	457
hruemsnd	22.75	6	170.46	49	0.54	2079
hruemsyd	10	4	170.46	33	0.36	615
hrueusnd	7.5	4	170.46	33	0.36	462
hrueusyd	3.5	2	170.46	20	0.22	131
Total	**1647.25**					**218239**
Sand- parendzinas						
splelsnd	5.0	12	10.98	87	0.95	52
Total	**5.0**					**52**
Brown earth						
belelsnd	12	24	185.72	156	1.71	3803
belemsnd	6	22	185.72	147	1.61	1792
bemelsnd	19	22	185.72	147	1.61	5674
bememsnd	1.75	20	185.72	134	1.47	476
Total	**38.75**					**11746**
Brown alluvial						
balelsnd	5.75	24	115.16	156	1.71	1130
balemsnd	9.25	22	115.16	147	1.61	1713
bamelsnd	7.25	22	115.16	147	1.61	1343
bamemsnd	6.5	20	115.16	134	1.47	1097
Total	**28.75**					**5283**
Brown Podzolic						
bplelsnd	541.5	20	118.2	134	1.47	93820
bplemsnd	523.75	18	118.2	123	1.35	83295
bpleusnd	0.75	16	118.2	111	1.21	108
bpmelsnd	2193.25	18	118.2	123	1.35	348807
bpmelsyd	4.75	16	118.2	111	1.21	682
bpmemsnd	1927.25	16	118.2	111	1.21	276601
bpmemsyd	6.5	14	118.2	99	1.08	832
bpmeusnd	23.5	14	118.2	99	1.08	3008
bpuelsnd	0.75	16	118.2	111	1.21	108
bpuelsyd	0.5	14	118.2	99	1.08	64
bpuemsnd	2	14	118.2	99	1.08	256
bpuemsyd	0.5	12	118.2	87	0.95	56
Total	**5225**					**807637**

Patch name	Area (ha)	AYC	Soil type carbon stock (tonne)	Tree and litter carbon stock (tonne / hectare)	TLO_{CS} / MOC_{TL}*	Soil organic carbon stock (tonnes)
a	**b**	**c**	**d**	**e (TLO_{CS})**	**f = e / 91.42**	**g = b x d x f**
Humic Brown Podzolic						
hpmelsnd	7.75	18	213.81	123	1.35	2230
hpmemsnd	3.25	16	213.81	111	1.21	844
hpuelsnd	1	16	213.81	111	1.21	260
hpuelsyd	2	14	213.81	99	1.08	463
hpuemsnd	4.25	14	213.81	99	1.08	984
hpuemsyd	1.75	12	213.81	87	0.95	356
hpueusnd	0.5	12	213.81	87	0.95	102
Total	**20.5**					**5238**
Ironpan stagnopodzols						
islelsnd	5.25	16	92.97	111	1.21	593
islemsnd	4.75	14	92.97	99	1.08	478
ismelsnd	270.25	14	92.97	99	1.08	27209
ismelsyd	0.75	12	92.97	87	0.95	66
ismemsnd	32.75	12	92.97	87	0.95	2898
ismemsyd	0.5	10	92.97	75	0.82	38
ismeusnd	0.25	10	92.97	75	0.82	19
isuelsnd	3.5	12	92.97	87	0.95	310
isuelsyd	2	10	92.97	75	0.82	153
isuemsnd	7	10	92.97	75	0.82	534
isuemsyd	0.75	8	92.97	63	0.69	48
isueusnd	0.75	8	92.97	63	0.69	48
Total	**328.5**					**32394**
Ferric stagnopodzols						
fslelsnd	4.25	16	192.05	111	1.21	991
fslemsnd	0.5	14	192.05	99	1.08	104
fsmelsnd	2434	14	192.05	99	1.08	506226
fsmelsyd	24	12	192.05	87	0.95	4387
fsmemsnd	1125.5	12	192.05	87	0.95	205709
fsmemsyd	8.25	10	192.05	75	0.82	1300
fsmeusnd	9.5	10	192.05	75	0.82	1497
fsuelsnd	4.25	12	192.05	87	0.95	777
fsuelsyd	7.5	10	192.05	75	0.82	1182
fsuemsnd	9.25	10	192.05	75	0.82	1457
fsuemsyd	5	8	192.05	63	0.69	662
Total	**3632**					**724291**
Cambic stagno gley						
cslelsnd	62.25	22	119.29	147	1.61	11941
cslemsnd	1.75	20	119.29	134	1.47	306
csmelsnd	458	20	119.29	134	1.47	80085
csmemsnd	36.75	18	119.29	123	1.35	5898
Total	**558.75**					**98230**

Patch name	Area (ha)	AYC	Soil type carbon stock (tonne)	Tree and litter carbon stock (tonne / hectare)	TLO_{CS} / MOC_{TL}*	Soil organic carbon stock (tonnes)
a	b	c	d	e (TLO_{CS})	f = e / 91.42	g = b x d x f
Cambic stagnohumic gley						
chlelsnd	2.25	14	129.93	99	1.08	317
chmelsnd	1337.25	12	129.93	87	0.95	165354
chmelsyd	4	10	129.93	75	0.82	426
chmemsnd	190.75	10	129.93	75	0.82	20333
chmemsyd	1.75	8	129.93	63	0.69	157
chuelsnd	0.25	10	129.93	75	0.82	27
chuelsyd	0.5	8	129.93	63	0.69	45
chuemsnd	0.25	8	129.93	63	0.69	22
Total	**1537**					**186681**
Alluvial gley						
aglelsnd	51.75	20	185.06	134	1.47	14038
aglemsnd	14.75	18	185.06	123	1.35	3673
agmelsnd	57	18	185.06	123	1.35	14193
agmemsnd	2	16	185.06	111	1.21	449
Total	**125.5**					**32353**
Sandy gley						
sglelsnd	64	20	89.25	134	1.47	8373
Total	**64**					**8373**
Humic gley						
hglelsnd	5	18	207.81	123	1.35	1398
hgmelsnd	145.75	16	207.81	111	1.21	36777
hgmemsnd	34.25	14	207.81	99	1.08	7708
Total	**185**					**45883**
Raw oligo amorphous peat						
rplelsnd	1	14	1200	99	1.08	1300
rpmelsnd	1428.5	12	1200	87	0.95	1631381
rpmelsyd	13.5	10	1200	75	0.82	13291
rpmemsnd	147.75	10	1200	75	0.82	145460
rpmemsyd	0.25	8	1200	63	0.69	207
rpmeusnd	0.25	8	1200	63	0.69	207
rpuelsnd	36.75	10	1200	75	0.82	36180
rpuelsyd	33.25	8	1200	63	0.69	27497
rpuemsnd	6.25	8	1200	63	0.69	5169
rpuemsyd	1	6	1200	49	0.54	643
rpueusnd	0.5	6	1200	49	0.54	322
Total	**1669**					**1861656**
Earthy eutro-amorphous peat						
eplelsnd	14.75	18	1200	123	1.35	23815
eplemsnd	7.5	16	1200	111	1.21	10928
Total	**22.25**					**34743**

$$*MOC_{TL} = \frac{\text{Sum of tree and litter carbon stocks per hectare for all yield classes}}{\text{Total number of yield classes concerned}}$$

$$= (20+33+49+63+75+87+99+111+123+134+147+156) / 12$$

$$= \mathbf{91.42}$$

Appendix 3.4.4 Estimation of organic carbon according to AYC for conifer plantations of the study area.

Patch Name	Area hectare	AYC	Tree C stock tonne/ha	Total Tree C tonnes	Litter C stock tonne/ha	Total litter C tonnes	Soil type C Stock tonne/ha	*TLO_{CS} / MOC_{TL}	Total Soil C tonnes	Total C stock tonnes
a	**b**	**c**	**d**	**e = bxd**	**f**	**g = bxf**	**h**	**i**	**j= bxhxi**	**k=e+g+j**
hrueusyd	3.50	2	15	53	5	18	170.46	0.22	131	
Sub total	**3.50**			**53**		**18**			**131**	**201**
hruemsyd	10.00	4	25	250	8	80	170.46	0.36	615	
hrueusnd	7.50	4	25	188	8	60	170.46	0.36	462	
Sub total	**17.50**			**438**		**140**			**1077**	**1654**
hrmemsyd	2.50	6	38	95	11	28	170.46	0.54	228	
hrmeusnd	17.25	6	38	656	11	190	170.46	0.54	1576	
hruelsyd	5.00	6	38	190	11	55	170.46	0.54	457	
hruemsnd	22.75	6	38	865	11	250	170.46	0.54	2079	
rpuemsyd	1.00	6	38	38	11	11	1200	0.54	643	
rpueusnd	0.50	6	38	19	11	6	1200	0.54	322	
Sub total	**49.00**			**1862**		**539**			**5305**	**7706**
chmemsyd	1.75	8	49	86	14	25	129.93	0.69	157	
chuelsyd	0.50	8	49	25	14	7	129.93	0.69	45	
chuemsnd	0.25	8	49	12	14	4	129.93	0.69	22	
fsuemsyd	5.00	8	49	245	14	70	192.05	0.69	662	
hrmelsyd	3.50	8	49	172	14	49	170.46	0.69	411	
hrmemsnd	350.50	8	49	17175	14	4907	170.46	0.69	41174	
hruelsnd	8.00	8	49	392	14	112	170.46	0.69	940	
isuemsyd	0.75	8	49	37	14	11	92.97	0.69	48	
isueusnd	0.75	8	49	37	14	11	92.97	0.69	48	
rpmemsyd	0.25	8	49	12	14	4	1200	0.69	207	
rpmeusnd	0.25	8	49	12	14	4	1200	0.69	207	
rpuelsyd	33.25	8	49	1629	14	466	1200	0.69	27497	
rpuemsnd	6.25	8	49	306	14	88	1200	0.69	5169	
Sub total	**411.00**			**20139**		**5754**			**76586**	**102479**
chmelsyd	4.00	10	58	232	17	68	129.93	0.82	426	
chmemsnd	190.75	10	58	11064	17	3243	129.93	0.82	20333	
chuelsnd	0.25	10	58	15	17	4	129.93	0.82	27	
fsmemsyd	8.25	10	58	479	17	140	192.05	0.82	1300	
fsmeusnd	9.50	10	58	551	17	162	192.05	0.82	1497	
fsuelsyd	7.50	10	58	435	17	128	192.05	0.82	1182	
fsuemsnd	9.25	10	58	537	17	157	192.05	0.82	1457	
hrlemsnd	1.00	10	58	58	17	17	170.46	0.82	140	
hrmelsnd	1215.50	10	58	70499	17	20664	170.46	0.82	169986	
ismemsyd	0.50	10	58	29	17	9	92.97	0.82	38	
ismeusnd	0.25	10	58	15	17	4	92.97	0.82	19	
isuelsyd	2.00	10	58	116	17	34	92.97	0.82	153	
isuemsnd	7.00	10	58	406	17	119	92.97	0.82	534	
rpmelsyd	13.50	10	58	783	17	230	1200	0.82	13291	
rpmemsnd	147.75	10	58	8570	17	2512	1200	0.82	145460	
rpuelsnd	36.75	10	58	2132	17	625	1200	0.82	36180	
Sub total	**1653.75**			**95918**		**28114**			**392024**	**516055**

Patch Name	Area hectare	AYC	Tree C stock tonne/ha	Total Tree C tonnes	Litter C stock tonne/ha	Total litter C tonnes	Soil type C Stock tonne/ha	*TLO_{CS} / MOC_{TL}	Total Soil C tonnes	Total C stock tonnes
a	b	c	d	e= bxd	f	g= bxf	h	i	j= bxhxi	k=e+g+j
bpuemsyd	0.50	12	68	34	19	10	118.2	0.95	56	
chmelsnd	1337.25	12	68	90933	19	25408	129.93	0.95	165354	
fsmelsyd	24.00	12	68	1632	19	456	192.05	0.95	4387	
fsmemsnd	1125.50	12	68	76534	19	21385	192.05	0.95	205709	
fsuelsnd	4.25	12	68	289	19	81	192.05	0.95	777	
hpuemsyd	1.75	12	68	119	19	33	213.81	0.95	356	
hpueusnd	0.50	12	68	34	19	10	213.81	0.95	102	
hrlelsnd	0.25	12	68	17	19	5	170.46	0.95	41	
ismelsyd	0.75	12	68	51	19	14	92.97	0.95	66	
ismemsnd	32.75	12	68	2227	19	622	92.97	0.95	2898	
isuelsnd	3.50	12	68	238	19	67	92.97	0.95	310	
rpmelsnd	1428.50	12	68	97138	19	27142	1200	0.95	1631381	
splelsnd	5.00	12	68	340	19	95	10.98	0.95	52	
Sub total	**3964.50**			**269586**		**75326**			**2011488**	**2356400**
bpmemsyd	6.50	14	78	507	21	137	118.2	1.08	832	
bpmeusnd	23.50	14	78	1833	21	494	118.2	1.08	3008	
bpuelsyd	0.50	14	78	39	21	11	118.2	1.08	64	
bpuemsnd	2.00	14	78	156	21	42	118.2	1.08	256	
chlelsnd	2.25	14	78	176	21	47	129.93	1.08	317	
fslemsnd	0.50	14	78	39	21	11	192.05	1.08	104	
fsmelsnd	2434.00	14	78	189852	21	51114	192.05	1.08	506226	
hgmemsnd	34.25	14	78	2672	21	719	207.81	1.08	7708	
hpuelsyd	2.00	14	78	156	21	42	213.81	1.08	463	
hpuemsnd	4.25	14	78	332	21	89	213.81	1.08	984	
islemsnd	4.75	14	78	371	21	100	92.97	1.08	478	
ismelsnd	270.25	14	78	21080	21	5675	92.97	1.08	27209	
rplelsnd	1.00	14	78	78	21	21	1200	1.08	1300	
	2785.75			**217289**		**58501**			**548949**	**824739**
agmemsnd	2.00	16	88	176	23	46	185.06	1.21	449	
bpleusnd	0.75	16	88	66	23	17	118.2	1.21	108	
bpmelsyd	4.75	16	88	418	23	109	118.2	1.21	682	
bpmemsnd	1927.25	16	88	169598	23	44327	118.2	1.21	276601	
bpuelsnd	0.75	16	88	66	23	17	118.2	1.21	108	
eplemsnd	7.50	16	88	660	23	173	1200	1.21	10928	
fslelsnd	4.25	16	88	374	23	98	192.05	1.21	991	
hgmelsnd	145.75	16	88	12826	23	3352	207.81	1.21	36777	
hpmemsnd	3.25	16	88	286	23	75	213.81	1.21	844	
hpuelsnd	1.00	16	88	88	23	23	213.81	1.21	260	
islelsnd	5.25	16	88	462	23	121	92.97	1.21	593	
Sub total	**2102.50**			**185020**		**48358**			**328339**	**561716**

Patch Name	Area hectare	AYC	Tree C stock tonne/ha	Total Tree C tonnes	Litter C stock tonne/ha	Total litter C tonnes	Soil type C Stock tonne/ha	*TLO_{CS} / MOC_{TL}	Total Soil C tonnes	Total C stock tonnes
a	**b**	**c**	**d**	**e= bxd**	**f**	**g= bxf**	**h**	**i**	**j= bxhxi**	**k=e+g+j**
aglemsnd	14.75	18	98	1446	25	369	185.06	1.35	3673	
agmelsnd	57.00	18	98	5586	25	1425	185.06	1.35	14193	
bplemsnd	523.75	18	98	51328	25	13094	118.2	1.35	83295	
bpmelsnd	2193.25	18	98	214939	25	54831	118.2	1.35	348807	
csmemsnd	36.75	18	98	3602	25	919	119.29	1.35	5898	
eplelsnd	14.75	18	98	1446	25	369	1200	1.35	23815	
hglelsnd	5.00	18	98	490	25	125	207.81	1.35	1398	
hpmelsnd	7.75	18	98	760	25	194	213.81	1.35	2230	
Sub total	**2853.00**			**279594**		**71325**			**483309**	**834228**
aglelsnd	51.75	20	108	5589	26	1346	185.06	1.47	14038	
bamemsnd	6.50	20	108	702	26	169	115.16	1.47	1097	
bememsnd	1.75	20	108	189	26	46	185.72	1.47	476	
bplelsnd	541.50	20	108	58482	26	14079	118.2	1.47	93820	
cslemsnd	1.75	20	108	189	26	46	119.29	1.47	306	
csmelsnd	458.00	20	108	49464	26	11908	119.29	1.47	80085	
sglelsnd	64.00	20	108	6912	26	1664	89.25	1.47	8373	
Sub total	**1125.25**			**121527**		**29257**			**198195**	**348978**
balemsnd	9.25	22	118	1092	29	268	115.16	1.61	1713	
bamelsnd	7.25	22	118	856	29	210	115.16	1.61	1343	
belemsnd	6.00	22	118	708	29	174	185.72	1.61	1792	
bemelsnd	19.00	22	118	2242	29	551	185.72	1.61	5674	
cslelsnd	62.25	22	118	7346	29	1805	119.29	1.61	11941	
Sub total	**103.75**			**12243**		**3009**			**22462**	**37714**
balelsnd	5.75	24	127	730	29	167	115.16	1.71	1130	
belelsnd	12.00	24	127	1524	29	348	185.72	1.71	3803	
Sub total	**17.75**			**2254**		**515**			**4933**	**7702**
Total	**15087.25**			**1205921**		**320853**			**4072798**	**5599572**

Appendix 4.2.1

Table showing features of the seven core AOGCMs and the experiments.
(IPCC-TGCIA, 1999)

	ECHAM4	HadCM2	CSIRO	CGCM1	GFDL	NCAR	CCSR
AGCM	2.8^0 x2.8^0 L19	2.5^0 x 3.75^0 L19	3.2^0 x 5.6^0 L9	3.7^0 x 3.7^0 L10	4.5^0 x 7.5^0 L9	4.5^0 x 7.5^0 L9	5.6^0 x 5.6^0 L20
OGCM	2.8^0 x2.8^0 L11	2.5^0 x 3.75^0 L20	3.2^0 x 5.6^0 L21	1.8^0 x 1.8^0 L29	4.5^0 x 3.75^0 L12	1^0 x 1^0 L20	2.8^0 x 2.8^0 L17
Features	Prognostic CLW, geostrophic ocean	Prognostic CLW, isopyncal ocean diffusion			No diurnal cycle, isopyncal ocean diffusion	No diurnal cycle	Prognostic CLW, explicit sulfate scattering
Flux correction	Monthly mean heat, fresh water, stress	Monthly mean heat, fresh water	Heat, fresh water, momentum	Heat, fresh water	Monthly mean heat, fresh water	None	Monthly mean heat, fresh water
Control CO_2	354 ppmv	323 ppmv	330 ppmv	295 ppmv	300 ppmv	330 ppmv	345 ppmv
Transient CO_2	1.0% yr^{-1} (compound)	1.0% yr^{-1} (compound)	0.9% yr^{-1}	1.0% yr^{-1}	1.0% yr^{-1} (compound)	1.0% yr^{-1} (linear)	1.0% yr^{-1} (compound)
Greenhouse Gases	CO_2: Historic 1860-1989 IS92a: 1990-2099	CO_2: Historic 1860-1989 IS92a: 1990-2099	CO_2: Historic 1881-1989 IS92a: 1990-2100	CO_2: Historic 1860-1989 IS92a: 1990-2100	CO_2: IS92a: 1958-2057	CO_2: Historic 1901-1989 IS92a: 1990-2036	CO_2: Historic 1860-1989 IS92a: 1990-2099
Greenhouse Gases + Sulphate Aerosols	CO_2: Historic 1860-1989 IS92a: 1990-2049 SO_4: Historic 1860-1989 IS92a: 1990-2049	CO_2: Historic 1860-1989 IS92a: 1990-2099 SO_4: Historic 1860-1989 IS92a: 1990-2099	CO_2: Historic 1881-1989 IS92a: 1990-2049 SO_4: Historic 1860-1989 IS92a: 1990-2100	CO_2: Historic 1900-1989 IS92a: 1990-2100 SO_4: Historic 1860-1989 IS92a: 1990-2100	CO_2: Historic 1766-1989 IS92a: 1990-2065 SO_4: Historic 1766-1989 IS92a: 1990-2065	CO_2: Historic 1901-1989 IS92a: 1990-2036 SO_4: Historic 1901-1989 IS92a: 1990-2036	CO_2: Historic 1890-1989 IS92a: 1990-2099 SO_4: Historic 1890-1989 IS92a: 1990-2099
Simulation length (yr)	Control: 240 Greenhouse: 240 Greenhouse +Aer: 240	Control: 240 Greenhouse: 240 Greenhouse +Aer: 240	Control: 219 Greenhouse: 219 Greenhouse +Aer: 219	Control: 200 Greenhouse: 200 Greenhouse +Aer: 200	Control: 1000 Greenhouse: 100 Greenhouse +Aer: 300	Control: 136 Greenhouse: 136 Greenhouse +Aer: 136	Control: 210 Greenhouse: 210 Greenhouse +Aer: 210
Warming (^{0}C) at CO_2 doubling	1.3	1.7	2.0	2.7	2.3	2.3 (est.)	2.4
2 x CO_2 sensitivity (^{0}C)	2.6	2.5	4.3	3.5	3.7	4.6	3.5

AOGCM: Atmosphere- ocean general circulation model AGCM: Atmosphere general circulation model; OGCM: Ocean general circulation model

Appendix 4.2.2: Species compositions, altitude and climate ranges for NVC woodlands for the Snowdonia National Park.

Species compositions with potential natural vegetation classifications for upland Snowdonia (Schumacher, 1997).

NVC	**Woodland compositions**
W4	*Betula pubescens - Molinia caeruea*
W7	*Alnus glutinosa - Fraxinus excelsior - Lysimachia nemorum*
W9	*Fraxinus excelsior - Sorbus aucuparia - Mercurialis perennis*
W11	*Quercus petraea - Betula pubescens - Oxalis acetosella*
W17	*Quercus petraea - Betula pubescens - Dicranum majus*

Altitudinal and climate ranges for the NVC species of the Snowdonia National Park (CABI, 1998).

Name of species	Altitude range (meter)	Mean annual rainfall (millimetre)	Mean annual temperature (^{0}C)	Mean maximum temperature in hottest month (^{0}C)	Mean minimum temperature in coolest month (^{0}C)
Quercus petraea (Matt.)	0 - 2000	400 - 2500	5 - 15	10 - 20	(-) 15 – (-) 8
Betula pubescens (Ehrh.)	0 - 2200	350 - 1800	(-) 6 - 14	10 - 18	(-) 25- 10
Fraxinus excelsior (L.)	0 - 1400	600 - 1000	7 - 13	20 - 30	(-) 5 - 6
Sorbus aucuparia (L.)	600 - 2100	500 - 1350	(-) 6 - 21	23 - 31	(-) 20 - (-) 2
Alnus glutinosa (L.)	0 - 2000	400 - 1300	1 - 18	15 - 25	(-) 30 - (-) 8

CABI 1998. *Forestry Compendium Global Module*. CDROM of UWB.

Appendix 4.3.1. Illustrates the flow charts of map processing in CCSA model generation.

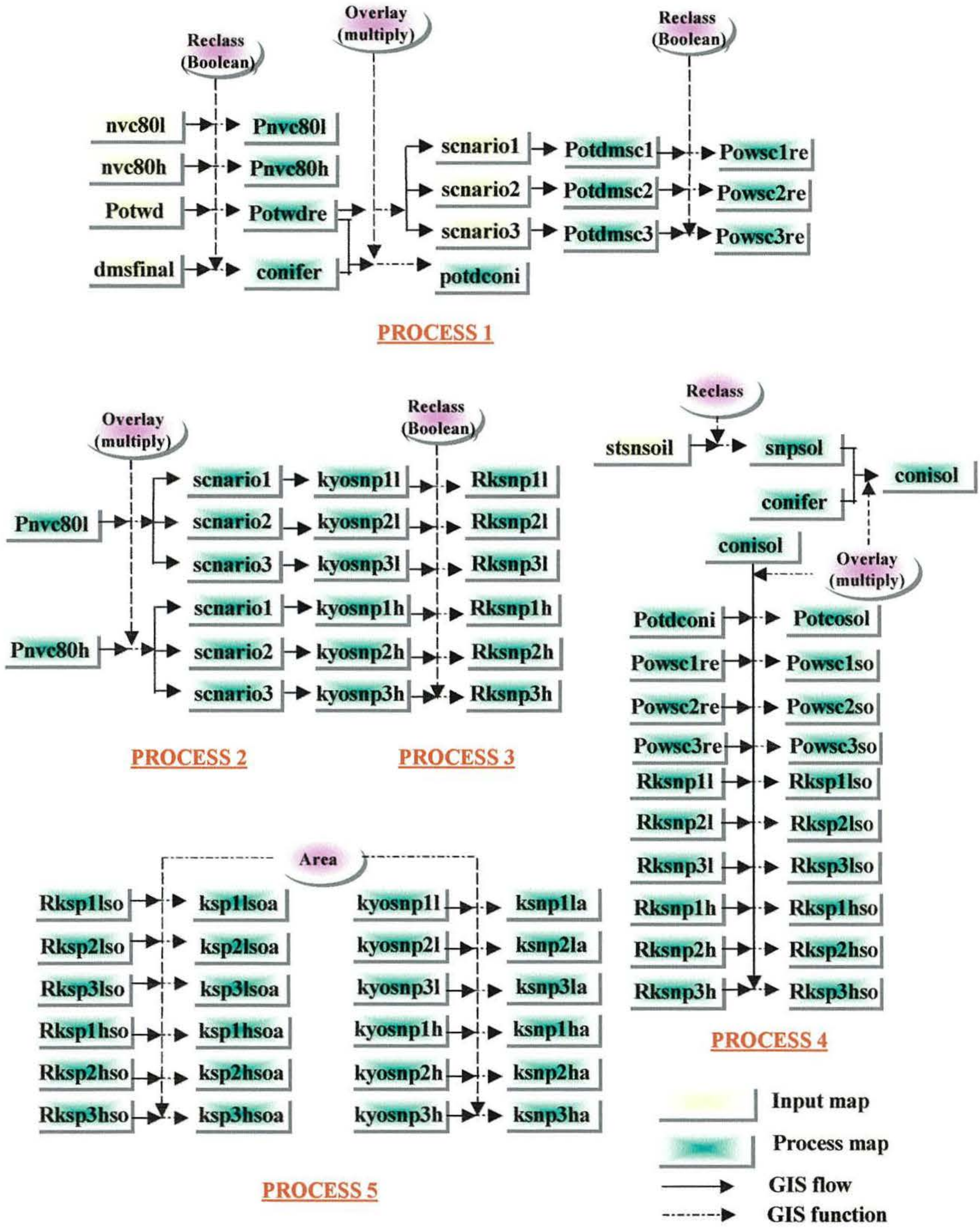


Figure 1 Describing the flow of GIS procedure for Process1,2,3,4 and 5 in CCSA model

Appendix 4.3.2: Macro languages for climate change scenario adoption (CCSA) model

Following input maps were used to run the climate change scenario adoption (CCSA) model:

Soil map of SNP – *snpsoilt* (SAFS net work), Altitude map of SNP – *snp50con* (SAFS net work), slope map of SNP – *snpslp* (SAFS net work), present annual temperature map – *snptemp* (Mulligan, 1999), present annual precipitation map – *snprain* (Mulligan, 1999), temperature maps for 2080 with low and high scenario of UKCIP – *temp80l* and *temp80h* (Mulligan, 1999), precipitation maps for2020 and 2080 with low and high scenario of UKCIP – *rain20l, rain20h* and *rain80h* (Mulligan, 1999). All maps were resampled before using in the model.

4.3.2.1 Resampling of input maps

resample	x	i	snpsoilt	stsnsoil	alamin	plane	m			
	1	0	245575	300325	299975	379425	1095	1589	1	1
resample	x	i	snp50con	tsnpalti	alamin	plane	m			
	1	0	245575	300325	299975	379425	1095	1589	1	1
resample	x	i	snpslp	tsnpslop	alamin	plane	m			
	1	0	245575	300325	299975	379425	1095	1589	1	1
resample	x	i	snprain	snprain1	alamin	plane	m			
	1	0	245575	300325	299975	379425	1095	1589	1	1
resample	x	i	snptemp	snptemp1	alamin	plane	m			
	1	0	245575	300325	299975	379425	1095	1589	1	1
resample	x	i	temp80l	temp80l1	alamin	plane	m			
	1	0	245575	300325	299975	379425	1095	1589	1	1
resample	x	i	temp80h	temp80h1	alamin	plane	m			
	1	0	245575	300325	299975	379425	1095	1589	1	1
resample	x	i	rain20l	rain20l1	alamin	plane	m			
	1	0	245575	300325	299975	379425	1095	1589	1	1
resample	x	i	rain20h	rain20h1	alamin	plane	m			
	1	0	245575	300325	299975	379425	1095	1589	1	1
resample	x	i	rain80h	rain80h1	alamin	plane	m			
	1	0	245575	300325	299975	379425	1095	1589	1	1

4.3.2.2 Boolean constraints

Soil

reclass x i snpsoilt **w4soil** 2 0 0 9 1 9 10 0 10 12 1 12 13 0 13 999 -9999
reclass x i snpsoilt **w7soil** 2 0 0 8 1 8 9 0 9 10 1 10 12 0 12 999 -9999
reclass x i snpsoilt **w9soil** 2 0 0 8 1 8 9 0 9 999 -9999
reclass x i snpsoilt **w11soil** 2 0 0 2 1 2 6 0 6 999 -9999
reclass x i snpsoilt **w17soil** 2 0 0 1 1 1 2 0 2 4 1 4 8 0 8 999 -9999

Slopes

reclass x i snpslp **w4slp** 2 0 0 1 1 1 3 0 3 999 -9999
reclass x i snpslp **w7slp** 2 0 0 1 1 1 3 0 3 999 -9999
reclass x i snpslp **w9slp** 2 0 0 3 1 3 13 0 13 999 -9999
reclass x i snpslp **w11slp** 2 0 0 3 1 3 13 0 13 999 -9999
reclass x i snpslp **w17slp** 2 0 0 3 1 3 10 0 10 999 -9999

Altitude
reclass x i snp50con **w4alt** 2 0 0 6 1 6 9 0 9 999 -9999
reclass x i snp50con **w7alt** 2 0 0 6 1 6 7 0 7 999 -9999
reclass x i snp50con **w9alt** 2 0 0 6 1 6 9 0 9 999 -9999
reclass x i snp50con **w11alt** 2 0 0 6 1 6 14 0 14 999 -9999
reclass x i snp50con **w17alt** 2 0 0 6 1 6 14 0 14 999 -9999
reclass x i snp50con **Upland** 2 0 0 6 1 6 23 0 23 999 -9999
Suitable landuse
reclass x i snplu80 **Suitlu** 2 0 0 6 1 6 10 0 10 12 1 12 15 0 15 19 1 19 21 0 21 999 -9999
Rainfall (W11 & W17 only)
reclass x i snprain **w11rain** 2 0 0 1 1 1 4 0 4 99 -9999
reclass x i snprain **w17rain** 2 0 0 4 1 4 99 –9999

4.3.2.3 Decision support files applied to MCE function

dW4	dW7	dW9	DW11	dW17
4	4	4	5	5
0	0	0	0	0
suitlu	suitlu	suitlu	Suitlu	Suitlu
w4soil	w7soil	w9soil	w11soil	w17soil
W4slp	W7slp	W9slp	W11slp	W17slp
W4alt	W7alt	W9alt	W11alt	W17alt
			w11rain	w17rain

4.3.2.4 Multi criteria evaluation (MCE).
MCE x potw4 dW4
MCE x potw7 dW7
MCE x potw9 dW9
MCE x potw11 dW11
MCE x potw17 dW17

4.3.2.5 Creation of a single potential woodland image (POTWD)
reclass x i potw7 potw7a 2 0 0 1 2 1 2 0 2 999 -9999
reclass x i potw9 potw9a 2 0 0 1 3 1 2 0 2 999 -9999
reclass x i potw11 potw11a 2 0 0 1 4 1 2 0 2 999 -9999
reclass x i potw17 potw17a 2 0 0 1 5 1 2 0 2 999 -9999
overlay x 7 potw4 potw7a potwa
overlay x 7 potwa potw9a potwb
overlay x 7 potwb potw11a potwc
overlay x 7 potwc potw17a ***potwd***

4.3.2.6 Reclass of mean annual temperature and annual precipitation scenarios for each NVC woodland type attributes

Boolean Constraints for W4 woodland

2080 low

reclass x i temp80l w4t80l 2 0 0 7 1 7 99 -9999

reclass x i rain20l w4r80l 2 0 0 3 1 3 5 0 5 99 -9999

2080 high

reclass x i temp80h w4t80h 2 0 0 7 1 7 99 -9999

reclass x i rain80h w4r80h 2 0 0 3 1 3 5 0 5 99 -9999

Boolean Constraints for W7 woodland

2080 low

reclass x i temp80l w7t80l 2 0 0 8 1 8 99 -9999

reclass x i rain20l w7r80l 2 0 0 3 1 3 4 0 4 99 -9999

2080 high

reclass x i temp80h w7t80h 2 0 0 8 1 8 99 -9999
reclass x i rain80h w7r80h 2 0 0 3 1 3 4 0 4 99 –9999

Boolean Constraints for W9 woodland

2080 low

reclass x i temp80l w9t80l 2 0 0 7 1 7 99 -9999
reclass x i rain20l w9r80l 2 0 0 3 1 3 5 0 5 99 -9999

2080 high

reclass x i temp80h w9t80h 2 0 0 7 1 7 99 -9999
reclass x i rain80h w9r80h 2 0 0 3 1 3 5 0 5 99 -9999

Boolean Constraints for W11 woodland

2080 low

reclass x i temp80l w11t80l 2 0 0 6 1 6 99 -9999
reclass x i rain20l w11r80l 2 0 0 3 1 3 4 0 4 99 -9999

2080 high

reclass x i temp80h w11t80h 2 0 0 6 1 6 99 -9999
reclass x i rain80h w11r80h 2 0 0 3 1 3 4 0 4 99 –9999

Boolean Constraints for W17 woodland

2080 low

reclass x i temp80l w17t80l 2 0 0 6 1 6 99 -9999
reclass x i rain20l w17r80l 2 0 0 4 1 4 7 0 7 99 -9999

2080 high

reclass x i temp80h w17t80h 2 0 0 6 1 6 99 -9999
reclass x i rain80h w17r80h 2 0 0 4 1 4 7 0 7 99 –9999

4.3.2.7 Decision support files

W4 woodland DSF

6	6
0	0
w4t80l	w4t80h
w4r80l	w4r80h
suitlu	suitlu
w4soil	w4soil
w4slp	w4slp
upland	upland

W7 woodland DSF

6	6
0	0
w7t80l	w7t80h
w7r80l	w7r80h
suitlu	suitlu
w7soil	w7soil
w7slp	w7slp
upland	upland

W9 woodland DSF

6	6
0	0
w9t80l	w9t80h
w9r80l	w9r80h
suitlu	suitlu
w9soil	w9soil
w9slp	w9slp
upland	upland

W11 woodland DSF

6	6
0	0
w11t80l	w11t80h
w11r80l	w11r80h
suitlu	suitlu
w11soil	w11soil
w11slp	w11slp
upland	upland

W17 woodland DSF

6	6
0	0
w17t80l	w17t80h
w17r80l	w17r80h
suitlu	suitlu
w17soil	w17soil
w17slp	w17slp
upland	upland

4.3.2.8 MCE analysis

W4	**W7**	**W9**
MCE x Fw480l d480l	MCE x Fw780l d780l	MCE x Fw980l d980l
MCE x Fw480h d480h	MCE x Fw780h d780h	MCE x Fw780h d780h
W11	**W17**	
MCE x Fw1180l d1180l	MCE x fw1780l d1780l	
MCE x Fw1180h d1180h	MCE x fw1780h d1780h	

4.3.2.9 Creation of potential woodland images for each scenario

2080 low
reclass x i fw780l tmp1 2 0 0 1 2 1 2 0 2 99 -9999
reclass x i fw980l tmp2 2 0 0 1 3 1 2 0 2 99 -9999
reclass x i fw1180l tmp3 2 0 0 1 4 1 2 0 2 99 -9999
reclass x i fw1780l tmp4 2 0 0 1 5 1 2 0 2 99 -9999
overlay x 7 fw480l tmp1 tmpa
overlay x 7 tmp2 tmpa tmpb
overlay x 7 tmp3 tmpb tmpc
overlay x 7 tmp4 tmpc **NVC80l**

2080 high
reclass x i fw780h tmp1 2 0 0 1 2 1 2 0 2 99 -9999
reclass x i fw980h tmp2 2 0 0 1 3 1 2 0 2 99 -9999
reclass x i fw1180h tmp3 2 0 0 1 4 1 2 0 2 99 -9999
reclass x i fw1780h tmp4 2 0 0 1 5 1 2 0 2 99 -9999
overlay x 7 fw480h tmp1 tmpa
overlay x 7 tmp2 tmpa tmpb
overlay x 7 tmp3 tmpb tmpc
overlay x 7 tmp4 tmpc **NVC80h**

4.3.2.10 Climate change scenario adoption (CCSA model)

Process 1

reclass	x	i	nvc80l	Pnvc80l	2	0	0	1	1	1	6	0	6	999	-9999
reclass	x	i	nvc80h	Pnvc80h	2	0	0	1	1	1	6	0	6	999	-9999
reclass	x	i	potwd	potwdre	2	0	0	1	1	1	6	0	6	999	-9999
reclass	x	i	dmsfinal	conifer	2	0	0	1	1	1	13	0	13	999	-9999
overlay	x	3	potwdre	conifer	potdconi										
overlay	x	3	potwdre	scnario1	potdmsc1										
overlay	x	3	potwdre	scnario2	potdmsc2										
overlay	x	3	potwdre	scnario3	potdmsc3										
reclass	x	i	potdmsc1	powsc1re	2	0	0	1	1	1	4	0	4	999	-9999
reclass	x	i	potdmsc2	powsc2re	2	0	0	1	1	1	4	0	4	999	-9999
reclass	x	i	potdmsc3	powsc3re	2	0	0	1	1	1	3	0	3	999	-9999

Process 2

overlay	x	3	Pnvc80l	scnario1	kyosnp1l
overlay	x	3	Pnvc80l	scnario2	kyosnp2l
overlay	x	3	Pnvc80l	scnario3	kyosnp3l
overlay	x	3	Pnvc80h	scnario1	kyosnp1h
overlay	x	3	Pnvc80h	scnario2	kyosnp2h
overlay	x	3	Pnvc80h	scnario3	kyosnp3h

Process 3

```
reclass  x i kyosnp1l  Rksnp1l   2 0 0 1 1 1 4 0 4 9999 -9999
reclass  x i kyosnp2l  Rksnp2l   2 0 0 1 1 1 5 0 5 9999 -9999
reclass  x i kyosnp3l  Rksnp3l   2 0 0 1 1 1 6 0 6 9999 -9999
reclass  x i kyosnp1h  Rksnp1h   2 0 0 1 1 1 4 0 4 9999 -9999
reclass  x i kyosnp2h  Rksnp2h   2 0 0 1 1 1 5 0 5 9999 -9999
reclass  x i kyosnp3h  Rksnp3h   2 0 0 1 1 1 6 0 6 9999 -9999
```

Process 4

```
reclass  x i stsnsoil  snpsol   3 consol
overlay  x 3 snpsol    conifer  conisol
overlay  x 3 potdconi  conisol  Potcosol
overlay  x 3 powsc1re  conisol  powsc1so
overlay  x 3 powsc2re  conisol  powsc2so
overlay  x 3 powsc3re  conisol  powsc3so
overlay  x 3 Rksnp1l   conisol  Rksp1lso
overlay  x 3 Rksnp2l   conisol  Rksp2lso
overlay  x 3 Rksnp3l   conisol  Rksp3lso
overlay  x 3 Rksnp1h   conisol  Rksp1hso
overlay  x 3 Rksnp2h   conisol  Rksp2hso
overlay  x 3 Rksnp3h   conisol  Rksp3hso
```

Process 5

Low scenario

```
area  x kyosnp1l   2 2 ksnp1la
area  x kyosnp2l   2 2 ksnp2la
area  x kyosnp3l   2 2 ksnp3la
```

High scenario

```
area  x kyosnp1h   2 2 ksnp1ha
area  x kyosnp2h   2 2 ksnp2ha
area  x kyosnp3h   2 2 ksnp3ha
```

Low scenario

```
area  x Rksp1lso   2 2 ksp1lsoa
area  x Rksp2lso   2 2 ksp2lsoa
area  x Rksp3lso   2 2 ksp3lsoa
```

High scenario

```
area  x Rksp1hso   2 2 ksp1hsoa
area  x Rksp2hso   2 2 ksp2hsoa
area  x Rksp3hso   2 2 ksp3hsoa
```

Appendix 4.3.3 : Map analysis and macros for carbon estimation and altitude effects for CCSA scenarios

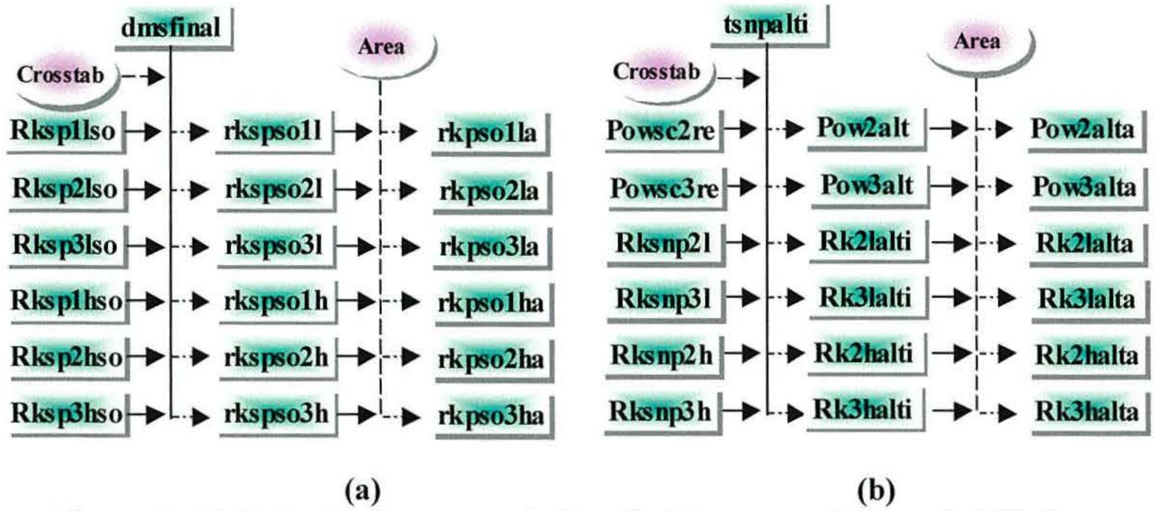


Figure 1. (a) illustrates the map analysis to find the areas of adjusted yield classes with respect to soil classes for three scenarios with high and low climate change and (b) describes the areas of the sites of present and future scenarios (2 and 3) according to the altitude class (***tsnpalti***: a map describing the altitude of the SNP).

Macro routines for the images:

A) For Figure 1 (a)

```
crosstab   x   Rksp1lso   dmsfinal   1   rkspso1l
crosstab   x   Rksp2lso   dmsfinal   1   rkspso2l
crosstab   x   Rksp3lso   dmsfinal   1   rkspso3l
crosstab   x   Rksp1hso   dmsfinal   1   rkspso1h
crosstab   x   Rksp2hso   dmsfinal   1   rkspso2h
crosstab   x   Rksp3hso   dmsfinal   1   rkspso3h
area   x   rkspso1l   2   2   rkpso1la
area   x   rkspso2l   2   2   rkpso2la
area   x   rkspso3l   2   2   rkpso3la
area   x   rkspso1h   2   2   rkpso1ha
area   x   rkspso2h   2   2   rkpso2ha
area   x   rkspso3h   2   2   rkpso3ha
```

B) For Figure 1 (b)

```
crosstab   x   powsc2re   tsnpalti   1   pow2alt
crosstab   x   powsc3re   tsnpalti   1   pow3alt
crosstab   x   Rksnp3l    tsnpalti   1   rk3lalti
crosstab   x   Rksnp3h    tsnpalti   1   rk3halti
crosstab   x   Rksnp4l    tsnpalti   1   rk4lalti
crosstab   x   Rksnp4h    tsnpalti   1   rk4halti
area   x   pow2alt    2   2   pow2alta
area   x   pow3alt    2   2   pow3alta
area   x   rk3lalti   2   2   rk3lalta
area   x   rk3halti   2   2   rk3halta
area   x   rk4lalti   2   2   rk4lalta
area   x   rk4halti   2   2   rk4halta
```

Appendix 4.4.1

Table 4.4.1.1 Estimation of organic carbon stock for PNBW (broadleaf woodland) using the sites of three scenarios of section 3.4.5 with *high climate change scenarios* of CCSA model.

Scenario	AYC	Area hectare	Tree C stock tonne	Litter C stock tonne	Tree + Litter C stock per hectare	Soil type C stock per hectare	*TLO_{CS} / MOC_{TL}	Soil C stock tonne	Total C stock tonne
a	b	c	d	e	f (TLO_{CS})	g	h = f / 84.83	i = c x g x h	j = d+e+i
Scenario1	2	0.75	25	15	53.5	170.46	0.63	81	121
	4	4.5	151	90	53.5	170.46	0.63	484	725
	10	9.75	327	195	53.5	170.46	0.63	1048	1570
Sub Total		**15**	**503**	**300**				**1613**	**2415**
Scenario2	8	98.25	6583	1965	87	170.46	1.03	17176	25724
	8	0.5	34	10	87	92.97	1.03	48	91
	8	0.75	50	15	87	192.05	1.03	148	213
	10	86.75	5812	1735	87	170.46	1.03	15166	22713
	10	3.5	235	70	87	92.97	1.03	334	638
	10	5	335	100	87	192.05	1.03	985	1420
	10	1	67	20	87	129.93	1.03	133	220
	12	0.25	17	5	87	118.2	1.03	30	52
	12	0.75	50	15	87	213.81	1.03	164	230
	12	9.75	653	195	87	92.97	1.03	930	1778
	12	344.5	23082	6890	87	192.05	1.03	67854	97825
	12	209.5	14037	4190	87	129.93	1.03	27917	46143
Sub Total		**760.5**	**50954**	**15210**				**130884**	**197047**
Scenario3	14	9.75	917	195	114	118.2	1.34	1549	2660
	14	1.5	141	30	114	213.81	1.34	431	602
	14	24	2256	480	114	92.97	1.34	2999	5735
	14	640.5	60207	12810	114	192.05	1.34	165306	238323
	16	437	41078	8740	114	118.2	1.34	69415	119233
	16	2.25	212	45	114	213.81	1.34	646	903
Sub Total		**1115**	**104810**	**22300**				**240346**	**367456**
Total		**1890.5**	**156266**	**37810**				**372842**	**566918**

* TLO_{CS} = Tree and litter carbon stock per hectare (tonne) for oak with 02, 04 and 06 yield class, MOC_{TL} = Mean of tree and litter organic carbon stocks per hectare which is derived from following equation:

$$MOC_{TL} = \frac{\text{Sum of tree and litter carbon stocks per hectare for all yield classes}}{\text{Total number of yield classes concerned}}$$

Here all yield class means yield class from 02 to 06, as the study area represents all these yield classes.

$MOC_{TL} = (53.5+87+114) / 3$ = **84.83**

Table 4.4.1.2 Estimation of organic carbon stock for PNBW (broadleaf woodland) using the sites of three scenarios of section 3.4.5 with *low climate change scenarios* of CCSA model.

Scenario	AYC	Area hectare	Tree C stock tonne	Litter C stock tonne	Tree + Litter C stock per hectare	Soil type C stock per hectare	*TLO_{CS} / MOC_{TL}	Soil C stock tonne	Total C stock tonne
a	b	c	d	e	f (TLO_{CS})	g	h = f / 84.83	i = c x g x h	j = d+e+i
Scenario1	2	0.75	25	15	53.5	170.46	0.63	81	121
	4	4.5	151	90	53.5	170.46	0.63	484	725
	10	10	335	200	53.5	170.46	0.63	1075	1610
Sub Total		**15.25**	**511**	**305**				**1640**	**2456**
Scenario2	8	95.5	6399	1910	87	170.46	1.03	16695	25004
	8	0.5	34	10	87	92.97	1.03	48	91
	8	0.75	50	15	87	192.05	1.03	148	213
	10	86.5	5796	1730	87	170.46	1.03	15122	22647
	10	3.5	235	70	87	92.97	1.03	334	638
	10	5	335	100	87	192.05	1.03	985	1420
	10	1	67	20	87	129.93	1.03	133	220
	12	0.25	17	5	87	118.2	1.03	30	52
	12	0.75	50	15	87	213.81	1.03	164	230
	12	9.75	653	195	87	92.97	1.03	930	1778
	12	344.5	23082	6890	87	192.05	1.03	67854	97825
	12	209.5	19693	4190	87	129.93	1.03	27917	51800
Sub Total		**757.5**	**56409**	**15150**				**130359**	**201918**
Scenario3	14	12.25	1152	245	114	118.2	1.34	1946	3342
	14	1.5	141	30	114	213.81	1.34	431	602
	14	24	2256	480	114	92.97	1.34	2999	5735
	14	640.5	60207	12810	114	192.05	1.34	165306	238323
	16	678.25	63756	13565	114	118.2	1.34	107736	185057
	16	2	188	40	114	213.81	1.34	575	803
Sub Total		**1358.5**	**127699**	**27170**				**278993**	**433862**
Total		**2131.25**	**184619**	**42625**				**410992**	**638236**

* TLO_{CS} = Tree and litter carbon stock per hectare (tonne) for oak with 02, 04 and 06 yield class, MOC_{TL} = Mean of tree and litter organic carbon stocks per hectare which is derived from following equation:

$$MOC_{TL} = \frac{\text{Sum of tree and litter carbon stocks per hectare for all yield classes}}{\text{Total number of yield classes concerned}}$$

Here all yield class means yield class from 02 to 06, as the study area represents all these yield classes.

$MOC_{TL} = (53.5+87+114) / 3$ = **84.83**

Appendix 4.4.2

Table 4.4.2.1 Estimation of organic carbon stock for conifer woodland using the sites of three scenarios of section 3.4.5 with *high climate change scenarios* of CCSA model.

Scenario	AYC	Area hectare	Tree C stock tonne	Litter C stock tonne	Tree + Litter C stock per hectare	Soil type C stock per hectare	*TLO_{CS} / MOC_{TL}	Soil C stock tonne	Total C stock tonne
a	b	c	d	e	f (TLO_{CS})	g	h = f / 91.42	i = c x g x h	j = d+e+i
Scenario1	2	0.75	11	4	20	170.46	0.22	28	43
	4	4.5	113	36	33	170.46	0.36	277	425
	10	9.75	371	107	49	170.46	0.54	891	1369
Sub Total		**15**	**494**	**147**				**1196**	**1837**
Scenario2	8	98.25	4814	1376	63	170.46	0.69	11541	17731
	8	0.5	25	7	63	92.97	0.69	32	64
	8	0.75	37	11	63	192.05	0.69	99	147
	10	86.75	5032	1475	75	170.46	0.82	12131	18638
	10	3.5	203	60	75	92.97	0.82	267	529
	10	5	290	85	75	192.05	0.82	788	1163
	10	1	58	17	75	129.93	0.82	107	182
	12	0.25	17	5	87	118.2	0.95	28	50
	12	0.75	51	14	87	213.81	0.95	153	218
	12	9.75	663	185	87	92.97	0.95	863	1711
	12	344.5	23426	6546	87	192.05	0.95	62962	92934
	12	209.5	14246	3981	87	129.93	0.95	25904	44131
Sub Total		**760.5**	**48861**	**13760**				**114875**	**177496**
Scenario3	14	9.75	761	205	99	118.2	1.08	1248	2213
	14	1.5	117	32	99	213.81	1.08	347	496
	14	24	1872	504	99	92.97	1.08	2416	4792
	14	640.5	49959	13451	99	192.05	1.08	133207	196617
	16	437	38456	10051	111	118.2	1.21	62716	111223
	16	2.25	198	52	111	213.81	1.21	584	834
Sub Total		**1115**	**91363**	**24294**				**200519**	**316175**
Total		**1890.5**	**140718**	**38200**				**316590**	**495508**

* TLO_{CS} = Tree and litter carbon stock per hectare (tonne) for a given species and yield class, MOC_{TL} = Mean of tree and litter organic carbon stocks per hectare which is derived from following equation:

$$MOC_{TL} = \frac{\text{Sum of tree and litter carbon stocks per hectare for all yield classes}}{\text{Total number of yield classes concerned}}$$

Here all yield class means adjusted yield class from 02 to 24, as the study area represents all these yield classes.

MOC_{TL} = (20+33+49+63+75+87+99+111+123+134+147+156) / 12 = **91.42**

Table 4.4.2.2 Estimation of organic carbon stock for conifer woodland using the sites of three scenarios of section 3.4.5 with *low climate change scenarios* of CCSA model.

Scenario	AYC	Area hectare	Tree C stock tonne	Litter C stock tonne	Tree + Litter C stock per hectare	Soil type C stock per hectare	TLO_{CS} / MOC_{TL}	Soil C stock tonne	Total C stock tonne
a	b	c	d	e	f (TLO_{CS})	g	h = f / 91.42	i = c x g x h	j = d+e+i
Scenario1	2	0.75	11	4	20	170.46	0.22	28	43
	4	4.5	113	36	33	170.46	0.36	277	425
	10	10	380	110	49	170.46	0.54	914	1404
Sub Total		**15.25**	**504**	**150**				**1219**	**1872**
Scenario2	8	95.5	4680	1337	63	170.46	0.69	11218	17235
	8	0.5	25	7	63	92.97	0.69	32	64
	8	0.75	37	11	63	192.05	0.69	99	147
	10	86.5	5017	1471	75	170.46	0.82	12096	18584
	10	3.5	203	60	75	92.97	0.82	267	529
	10	5	290	85	75	192.05	0.82	788	1163
	10	1	58	17	75	129.93	0.82	107	182
	12	0.25	17	5	87	118.2	0.95	28	50
	12	0.75	51	14	87	213.81	0.95	153	218
	12	9.75	663	185	87	92.97	0.95	863	1711
	12	344.5	23426	6546	87	192.05	0.95	62962	92934
	12	209.5	14246	3981	87	129.93	0.95	25904	44131
Sub Total		**757.5**	**48712**	**13717**				**114517**	**176946**
Scenario3	14	12.25	956	257	99	118.2	1.08	1568	2781
	14	1.5	117	32	99	213.81	1.08	347	496
	14	24	1872	504	99	92.97	1.08	2416	4792
	14	640.5	49959	13451	99	192.05	1.08	133207	196617
	16	678.25	59686	15600	111	118.2	1.21	97339	172625
	16	2	176	46	111	213.81	1.21	519	741
Sub Total		**1358.5**	**112766**	**29889**				**235397**	**378052**
Total		**2131.25**	**161981**	**43756**				**351133**	**556870**

* TLO_{CS} = Tree and litter carbon stock per hectare (tonne) for conifer with yield class, MOC_{TL} = Mean of tree and litter organic carbon stocks per hectare which is derived from following equation:

$$MOC_{TL} = \frac{\text{Sum of tree and litter carbon stocks per hectare for all yield classes}}{\text{Total number of yield classes concerned}}$$

Here all yield class means adjusted yield class from 02 to 24, as the study area represents all these yield classes.

MOC_{TL} = (20+33+49+63+75+87+99+111+123+134+147+156) / 12 = **91.42**

Appendix 5.4.1 **Carbon emission in Bangladesh (1972 - 1996)** (Marlend *et al.*, 1999)

(In thousand metric tons of carbon)

YEAR	TOTAL PROD. OF CO2	PROD. OF CO_2 GAS FUELS	PROD. OF CO_2 LIQUID FUELS	PROD. OF CO_2 SOLID FUELS	PROD. OF CO_2 GAS FLARING	PROD. OF CO_2 CEMENT MANU.	NATIONAL PER CAPITA PRODUCTION OF CO_2	PROD. OF CO_2 BUNKER FUELS
1972	926	195	632	97	0	3.1	0.01	23
1973	1204	312	762	126	0	4.1	0.02	31
1974	1256	377	755	112	0	11.8	0.02	19
1975	1307	263	892	129	0	22.9	0.02	21
1976	1504	385	975	122	0	21.3	0.02	19
1977	1572	431	962	137	0	41.7	0.02	25
1978	1629	457	1011	115	0	46.0	0.02	33
1979	1806	523	1141	98	0	43.8	0.02	26
1980	2083	605	1311	122	0	45.6	0.02	51
1981	2163	666	1323	127	0	46.9	0.02	66
1982	2345	864	1283	155	0	44.4	0.03	39
1983	2246	961	1160	83	0	41.7	0.02	21
1984	2483	1219	1195	32	0	37.1	0.03	33
1985	2768	1388	1296	51	0	32.7	0.03	22
1986	3097	1565	1416	77	0	39.7	0.03	15
1987	3199	1618	1418	121	0	42.2	0.03	13
1988	3657	1910	1600	104	0	42.3	0.03	13
1989	3629	2024	1535	28	0	42.6	0.03	13
1990	4192	2068	1787	291	0	45.8	0.04	9
1991	4303	2472	1700	93	0	37.4	0.04	4
1992	4417	2622	1670	87	0	37.1	0.04	0
1993	4670	2836	1764	33	0	37.4	0.04	0
1994	4991	3131	1822	0	0	38.1	0.04	0
1995	5713	3631	2045	0	0	38.1	0.05	10
1996	6266	3897	2330	0	0	38.8	0.05	12