APFNet Tools for Forestry under a Changing Climate

Edited by

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Preface

As Part of its capacity building program, the Asia-Pacific Network (APFNet) for Sustainable Forest Management and Rehabilitation sponsored its sixth workshop under the theme “Strategies and Approaches for Sustainable Management in Changing Climate”, which took place in Kunming, China in July 2013. Senior officials from 12 economies exchanged views about the challenges and opportunities associated with improving forest management including the establishment of appropriate management regulations and management plans for combating climate change in the region.

In the past few decades, many economies in the Asia-Pacific region, with the aid of supportive legislation, have been implementing certification schemes, strengthening institutional capacity and developing monitoring systems to track progress as they move toward sustainable forest management. However, a lake of adequate training and insufficient resources still pose serious constraints to achieving sustainable forest management.

Discussion during the workshop generated innovative ideas on how best to address a number of forest management issues in the region, including better ways to balance development with protection - the theme of the first APEC ministerial meeting on forestry, which took place in Beijing in September 2011.

APFNet is pleased to share this compilation of modeling tools for forestry under a changing climate from the Kunming workshop. We hope that readers find the information helpful in terms of assisting with efforts to improve the situation in their respective economies. Last but not least, we would like to thank all the authors and editors from the University of British Columbia, for their contribution.

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List of Abbreviations and Acronyms

3-PG	Physiological Principles in Predicting Growth model
AET	Actual Evapotranspiration
AGBio	Above Ground Biomass
ANUSPLIN	A Software developed by Australian National University using thin plate smoothing splines improves the interpolation of climate data
APEC	Asia-Pacific Economic Cooperation
APFNet	Asia-Pacific Network
BC	British Columbia
BEC	Biogeoclimatic Ecosystem Classification
BGBio	Below Ground Biomass
BIOME-BGC	BioGeochemical Cycles model
C	Carbon
CBM-CFS3	Carbon Budget Model-Canadian Forest Sector 3
CENTURY	A model can simulates the long-term dynamics of carbon , nitrogen, phosphorus, and sulfur for different plant-soil systems
CGCM3	Canadian third generation of Coupled Global Climate Model
ClimateAP	A model that can be used to downscale historical and future climate data for Asia-Pacific
ClimateWNA	A model that can be used to downscale historical and future climate data for Western North America
CO2FIX	An ecosystem-level simulation model that quantifies the C stocks and fluxes in the forest
DBH	Tree Diameter at Breast Height
DOM	Dead Organic Matter
EDC's	Electronic Data Collectors
EFISCEN	European Forest Information Scenario Model
FAO	Food and Agriculture Organization

FIP	Forest Inventory Program
FORECAST	Forestry and Environmental Change Assessment
FORECAST Climate	An extension of the FORECAST model
ForWaDy	Forest Water Dynamics Model
FSC	Forest Stewardship Council
GCMs	General Circulation Models
GHG	Green House Gas
GIS	Geographic information system
HWP	Harvest Wood Product
IPCC	Intergovernmental Panel on Climate Change
ITTO	International Tropical Timber Organization
IUFRO	International Union of Forest Research Organizations
LANDIS	Landscape, Disturbance and Succession
LAO PDR	Lao People's Democratic Republic
LULUCF	Land Use, Land-Use Change and Forestry
NEP	Net Ecosystem Production
NFPs	National Forest Programs
NGOs	Non-Governmental Organizations
NPP	Net Primary Productivity
NTHLB	Non-Timber Harvest Land Base
OAFs	Operational Adjustment Factors
OOB	Out Of Bag
PEF	Endorsement of Forest Certification
PET	Potential Evapotranspiration
PNG	Papua New Guinea
PRSIM	Parameter-elevation Regressions on Independent Slopes Model
REDD	Reduced Emissions from Deforestation and Forest Degradation
RF	Random Forests
Rh	Autotrophic Respiration

RIL	Reduced Impact Logging
SD	System Dynamic
SDM	Species Distribution Model
SFM	Sustainable Forest Management
TACA	Tree And Climate Assessment Model
TACA-EM	One Variant in TACA model that models establishment and growth
TACA-GEM	One Variant in TACA model that models seed dormancy and germination
TASS	Tree And Stand Simulator
TDI	Transpiration Deficit Index
TEM	Terrestrial Ecosystem Model
TFRK	Traditional Forest-Related Knowledge
THLB	Timber Harvest Land Base
TIPSY	Table Interpolation Program for Stand Yields
UBC	University of British Columbia
UNCED	United Nations Conference on Environment and Development
UNEP	United Nations Environment Program
UNFCCC	United Nations Framework Convention on Climate Change
VDYP7	Variable Density Yield projection version 7
WinTIPSY	An interactive user interface designed for TIPSY
WinVDYP7	An interactive user interface designed for VDYP7
WorldClim	A set of global climate grids with a spatial resolution of about 1 square kilometer

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Chapter 1. Overview of Issues and Challenges for Forestry in the Asia-Pacific Region

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An Overview of the Asia-Pacific Region

There are 4 sub-regions including 49 countries in the Asian-Pacific region (FAO 2011) (Figure 1.1 and Table 1.1). This region extends from Pakistan in the west to the small island states in the Pacific in the east, and from the north of Mongolia to the southern borders of Australia and New Zealand (Waggener & Lane 1997), covering about 2.8 billion hectares of land area (roughly 22 percent of world's land area). Around 60 percent of the world population lives there, including 70 percent of the world's poor (UNEP 2011).

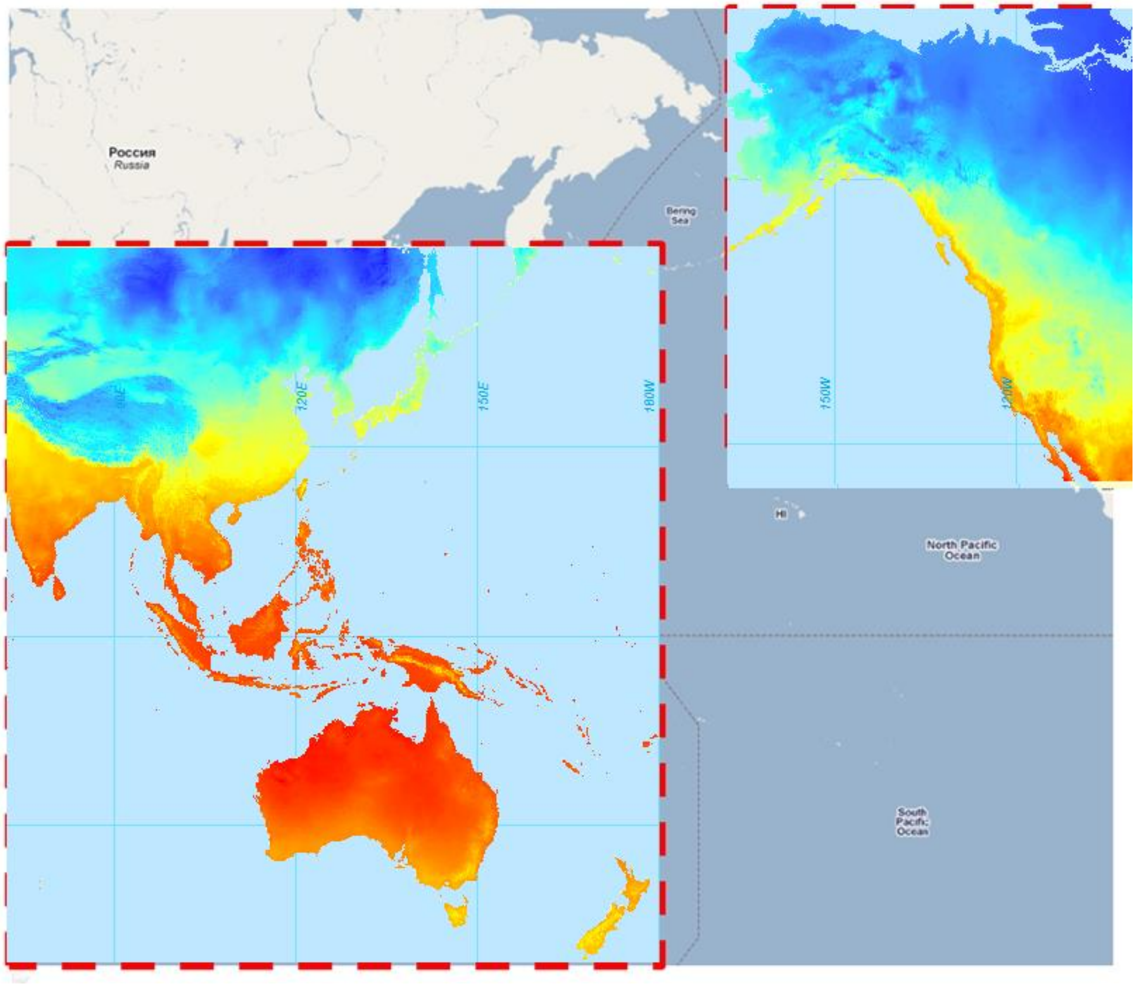

Figure 1.1 The Asia-Pacific Region (Source: http://asiapacific.forestry.ubc.ca/)

Table 1.1 Sub-regions and countries in each sub-region (adapted from FAO (2010a))

Sub-regions	Countries
East Asia	China, Democratic People's Republic of Korea, Japan, Mongolia, Republic of Korea;
South Asia	Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, Sri Lanka;
Southeast Asia	Brunei, Cambodia, Indonesia, Lao People's Democratic Republic, Malaysia, Myanmar, Philippines, Singapore, Thailand, Timor-Leste, Viet Nam;
Oceania	American Samoa, Australia, Cook Islands, Federated States of Micronesia, Fiji, French Polynesia, Guam, Kiribati, Marshall Islands, Nauru, New Caledonia, New Zealand, Niue, Norfolk Island, Northern Mariana Islands, Palau, Papua New Guinea, Pitcairn, Samoa, Solomon Islands, Tokelau, Tonga, Tuvalu, Vanuatu, Wallis and Futuna Islands

Forest Resources in the Asia-Pacific Region

Forest Area and Types

The total forest area in the Asia-Pacific region is estimated at 740 million hectares (FAO 2010b), representing around 18.3 percent of the global forest area and accounting for slightly less than one-third of the regional land area (FAO 2011) (Figure 1.2). Due to the relative high population, this region is the least forested region in the world on a per capita basis, with about 0.2 hectares per person (FAO 2010b). In addition to forest area, the Asia-Pacific region also has around 312 million hectares of other wooded land; Australia and China account for 76 percent of the other wooded land.

The distribution of forest area is quite uneven in the region; 71 percent of the forests in the region are in the following 4 countries: China, Australia, Indonesia and India (Figure 1.3, Table 1.2). Six countries in the region reported a forest cover of less than 10 percent of their total land area and among these, two countries (Nauru and Tokelau) reported no forest at all (FAO 2011). There is a significant difference between the Asian part of this region and Pacific sub-region in term of the forest area per capital. In the Asian part, there is 0.15 hectares of forest per capita on average, while for Pacific sub-region the number is 6.3 hectares per capita (FAO 2011).

Because of the wide geographical range, the forest types in this region show a great variety. The Asia-Pacific region covers 4 climatic zones: boreal, arid and semi-arid, tropical and temperate (UNFCCC 2007), which leads to a mix of temperate, boreal, subtropical and tropical forests.

Based on the different degree of human intervention, the forest area can be further divided into primary, modified, naturally regenerated, and planted forests. The modified naturally regenerated forest occupies the largest portion in this region (FAO 2011) (Figure 1.4).

Figure 1.2 Distribution of forests and woodlands in Asia-Pacific region (adapted from FAO (2010a))

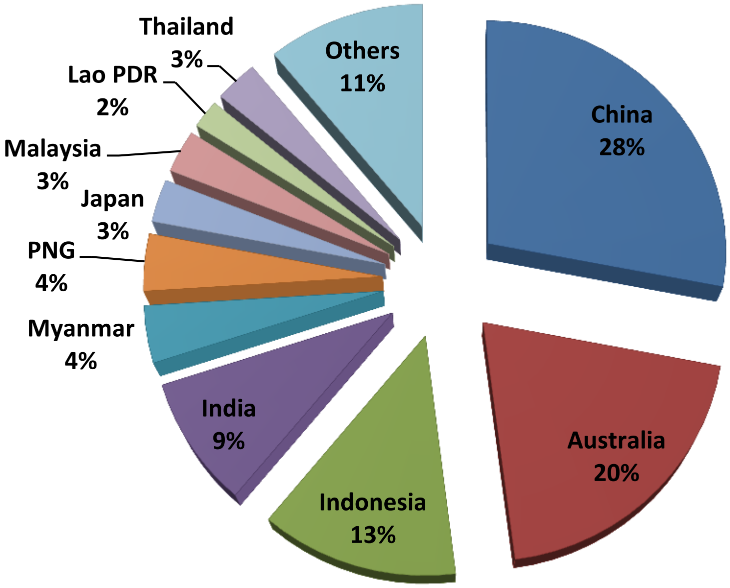

Figure 1.3 Distribution of forest area in the Asia-Pacific Region, based on countries (modified from FAO (2010a))

Table 1.2 Distribution of forest area in the Asia-Pacific Region, based on sub-regions (modified from FAO (2010a))

Sub-regions	Forest area 2010 (million area)	Share of the Asia-Pacific forests (%)	Share of the global forest (%)	Share of the global population (%)
East Asia	255	34.4	6.3	22.6
Southeast Asia	214	28.9	5.3	8.5
Oceania	191	25.9	4.7	0.5
South Asia	80	10.8	2.0	23.4
Asia-Pacific	740	100	18.4	55.1

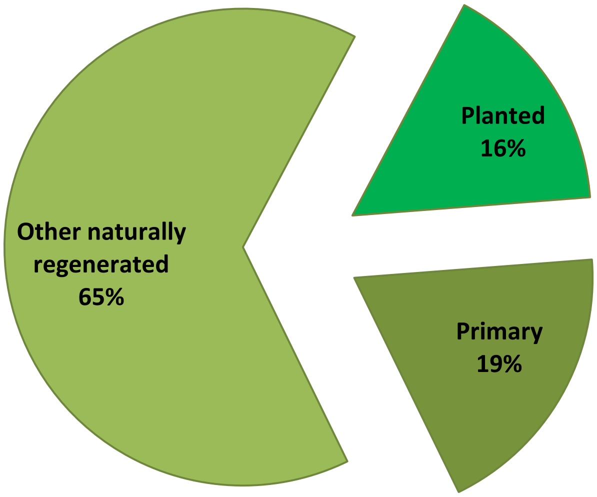

Figure 1.4 Characteristics of Asia-Pacific forests based on human intervention (modified from FAO (2010a))

Change in Forest Area

The total forest area declined by 0.7 million hectares per year from 1990 to 2000 (FAO 2011); however, the area increased at a rate of 0.5 million hectares annually since 2000 (Figure 1.5). The change is very uneven among countries. Some countries, including Cambodia, Indonesia, Myanmar and Papua New Guinea, reported large forest loss in the last decade. The main contributor to the increase in forest area in the region was China, where a large scale afforestation program increased the forest area significantly since 2000. If China's forest area increase is excluded, the deforestation rate in the remaining countries has remained more or less unchanged since 1990.

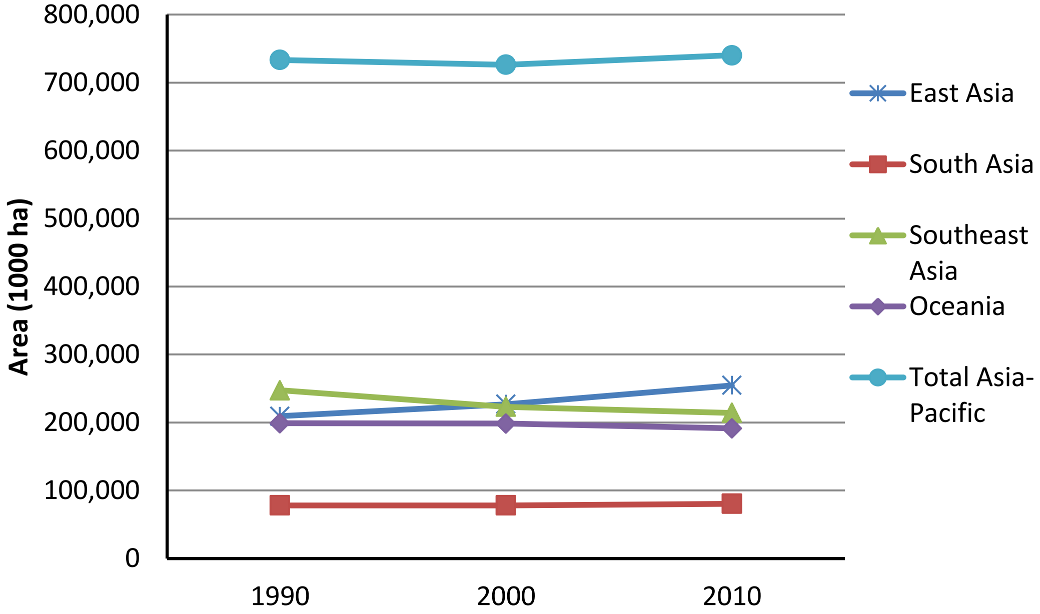

Figure 1.5 Changes of forest areas in Asia-Pacific region from 1990 to 2010 (FAO 2011)

Countries in Asia-Pacific region can be divided into 3 groups with respect to changes in forest cover over time (FAO 2010c): (1) in countries where agriculture is highly important, the pressure from forest conversion is high; (2) in developing countries where industrialization is considered a priority, mining, urbanization and infrastructure construction are the main causes for deforestation; and (3) in developed countries, strong policy incentive is provided for forest conservation to enhance the ecosystem services function and forest resources productivity from forests.

Forest Management in the Asia-Pacific Region

As was mentioned above, forests in the Asia-Pacific region can be divided into primary forests, modified natural forests and planted forests. Primary forests make up 19 percent of the total forest area, while modified natural forests make up 65 percent of the total, reflecting the intense human pressure. Planted forests make up the remaining16 percent of the forest area, with a focus mainly on wood and non-timber products (FAO 2010b) (Figure 1.4). Forest management is much more intensive in the Asia-Pacific region compared with the world average.

Natural Forest

Natural forests can be divided into protection forests and production forests. Relatively easily accessible areas with a high proportion of marketable species are more likely to be managed for wood production. Although the dependence on natural forests as a source of wood supply is declining, they remain an important source of revenue for several countries. Overall, the extent of natural forests managed sustainably remains very low (FAO 2010b). In general, there are three approaches to utilizing natural forests in the Asia-Pacific region (Table 1.3): intensive logging; sustained yield management; and banning logging.

Table 1.3 Different forest management approaches to natural forest in Asia-Pacific region (FAO 2010a)

Approaches	Explanations
Intensive logging	Logging activities which giving very little attention to the long-term sustainability of wood production and provision of ecosystem services.
Sustained yield management	Forest management which adopting a selective felling system (or variants) aiming to balance production and protection objectives.
Banning logging	Outright bans on logging in response to growing demand for ecosystem services.

To achieve better management in the natural forest sector, several steps have been taken including:

Reduced impact logging (RIL) has been promoted for the last two decades. Although RIL is economically viable in the long term, its adoption is very limited. Conventional logging is easier and commercially more profitable in the short term; hence, most concession holders and logging crews are less willing to adopt RIL. It requires substantial investments in planning, including training of logging crews. In particular, subcontracting various tasks, with maximizing short-term profits as the main consideration, usually discourages the adoption of RIL.

Certification aims to create a separate market for products from sustainably managed areas, providing an incentive to move away from unsustainable production. However, obtaining certification often entails significant costs to fulfill the stipulated criteria, as well as the costs associated with third party verification. While certification enhances market access, to date, price premiums have not been commensurate with the additional costs involved. For countries applying only rudimentary formal management to their forests, reaching a level that will make them eligible for certification will require significant changes in management practices entailing substantial expenditure and, often, significant reductions in volumes of wood extracted and potential revenues. Consequently, the extent of adoption of certification remains extremely low. The Asia-Pacific region has about 5 percent of the 306 million hectares of certified forests in the world, mainly in Australia, New Zealand, Malaysia and Indonesia (ITTO 2008). Two principal international programmes for certifying sustainable forest management are operational in the region. These are the Forest Stewardship Council (FSC) system and the Programme for Endorsement of Forest Certification (PEFC). In addition, several countries have developed their own certification systems, often drawing on the principles outlined by the FSC and PEFC. The most notable of these national certification systems are those of Indonesia, Malaysia, Myanmar, New Zealand and Australia.

In 2008, 4.4 million hectares of forest were certified under the Forest Stewardship Council (FSC) scheme in the Asia-Pacific region. The area is divided relatively evenly between natural forests (28 percent), semi-natural and mixed plantation and natural forests (34 percent) and plantation forests (37 percent). Sixty-nine percent of the total area is divided between three countries: China, New Zealand and Indonesia. Smaller areas exist in Australia, Japan and Malaysia. Growth rates in areas certified have been high in recent years in China and Indonesia, whereas in the Pacific, rates of increase have been much lower and in South Asia the area certified remains negligible (Figure 1.6).

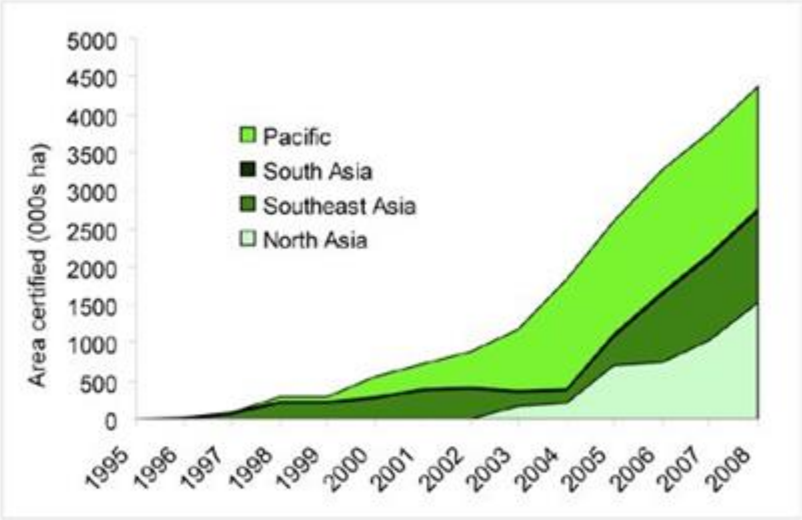

Figure 1.6 Area of FSC-certified forest in each sub-region (adapted from FAO (2010a)

Partial or total bans on wood production from natural forests have been adopted in several countries. Often natural calamities, such as floods and landslides have triggered such actions (for example, in China and Thailand). Even in countries where natural forests remain important sources of wood supply, large portions of forests have been excluded from wood production, giving them protected status.

Several countries in the Asia-Pacific region have significantly reduced their dependence on natural forests as a source of wood supply. For example, New Zealand obtains almost all of its wood supply from plantations and all natural forests are set aside exclusively for provision of ecosystem services. In the case of Sri Lanka, no logging is allowed in natural forests. Partial or total bans on logging exist in other countries, including China, India, Pakistan, Philippines, Thailand and Viet Nam.

As management of natural forests has become technically and economically more challenging, wood production has shifted towards planted forests.

Planted Forest

Planted forests in the Asia-Pacific region make up about 45 percent of global planted forests, with a total area of 120 million hectares. The annual growth rate in the region for planted forests has been about 2.2 percent from 2005 to 2010 (Table 1.4).

Table 1.4 Change of planted forest area in the Asia-Pacific region (FAO 2010b)

	Area of planted forests (million hectares)				**Annual change (%)**		
	1990	2000	2005	2010	1990-2000	2000-2005	2005-2010
Asia-Pacific	68.8	90.6	107.5	119.9	2.79	3.50	2.20
World	171.3	214.6	243.0	264.0	2.28	2.51	1.67

Key features of planted forests in the Asia-Pacific region (FAO 2010a) include:

- **A few countries (China, Viet Nam, Thailand, India, Indonesia, Japan and Australia) account for most of the increase of planted forest in the region.** Among these countries, China is the dominant force in planted forests. In 2010, China accounted for 64 percent of planted forests in the Asia-Pacific region and, over the preceding five years, 80 percent of the regional expansion in planted forests was in China. China's rapid expansion of plantations is based on highly focused, state-supported programmes.

- Most of the early efforts in forest plantation establishment focused on slow growing, long rotation species aimed to produce saw and veneer logs. Since 1980, there has been **a significant shift to short rotation fast-growing species**, mainly intended to produce pulp and other fiber products. Changes in wood-processing technologies enabling the use of small dimension logs have particularly influenced the choice of species and management practices, including rotation age.

- Historically, most plantations were under public ownership and management. However, this is changing in view of the **increasing involvement of corporate investors, local communities and smallholders**. In particular, there was a significant expansion of the area of planted forests under smallholder ownership between 1990 and 2005, with East Asia accounting for a large part of the increase (Figure 1.7).

- Stagnation in planted forest areas under public sector management is indicative of larger institutional and environmental challenges. The replacement of natural forests with plantations is slowing down as a result of increasing emphasis on environmental protection. Future expansion of plantations will be largely driven by the private sector, including smallholders, with commercial viability being a major consideration.

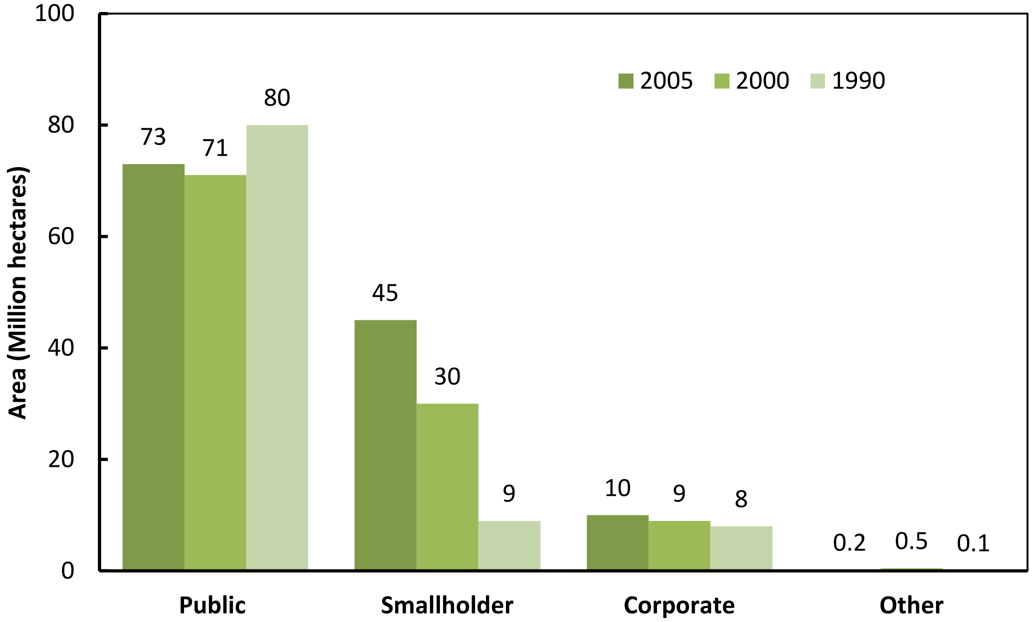

Figure 1.7 Change of planted forest ownership in Asia-Pacific region (modified from FAO (2010a))

Forest Policies Changes

Forest policies in the Asia-Pacific region have undergone major changes, involving a shift from timber-focused management to multiple-use management that gives due attention to a wide range of goods and services. In many cases, provision of ecosystem services has become a major thrust. Economic growth, globalization, trade liberalization and UNCED-related attention on sustainable development have all directly and indirectly influenced forest policies. Some key trends in forest policies include:

- Increased thrust on ecological aspects with provision of ecosystem services gaining primacy.
- Emphasis on increased involvement of stakeholders in forest management, including in forest policy formulation.

A number of internal and external factors have contributed to these changes. Increased pressure from growing populations has undermined the efficacy of traditional approaches to resource management, compelling public sector forest agencies to involve local communities and other players. Major policy changes have often been made in response to natural disasters, as in the case of logging bans in the context of floods and landslides.

Almost all countries in the Asia-Pacific region have adopted sustainable forest management as the main objective of their forest policies, giving due consideration to social, economic and environmental dimensions. Several countries have shifted their orientation from timber production to broader sustainable forest management. In China, for example, one of the main policy objectives is environmental protection and restoration. India, Indonesia and Viet Nam have implemented major reforestation and afforestation projects, focusing on environmental improvement, reflecting a shift in policy objectives. However, establishing trade-offs between competing objectives remains challenging. In the quest for rapid economic growth, extraction of minerals, energy production and infrastructure development have become major threats to forests; however, forest policies seldom provide a robust framework to deal with the changing situation (Table 1.5).

In many countries actual implementation of policies based on sustainable forest management has been weak because of field-level issues including high demand for forest land and forest resources, limited sources of alternative employment and low human resources capacity. Poor governance and low demand for alternative outcomes, for example greater production of environmental services, has also played a part. Similarly, permanent forest estates have often not been demarcated, agricultural frontiers have continued to advance and uncontrolled logging has often remained widespread.

In addition to forest policies, a plethora of extra-sectoral policies impinge on forests and forestry. For example, policies dealing with biodiversity, climate change mitigation, protection of wildlife and desertification control all transcend traditional sectoral boundaries. To some extent this has fragmented forestry agendas all the more so when several institutions are involved in policy implementation. Often such overlap mirrors the international situation, where almost every new convention also entails the creation of a new institution.

More importantly, policies in other sectors (agriculture, industry, energy, rural development, trade, etc.) heavily influence the forest sector, although these policies are usually primarily directed at issues far outside the forest sector. While there is considerable awareness about the impact of extra-sectoral policies on forests and forestry (and vice versa), difficulties persist in resolving intra-sectoral issues. In the event of conflicting objectives, forest policy objectives are often superseded by other policies that may appear to more directly and immediately affect human welfare.

Issues and Challenges of a Changing Climate in the Asia Pacific Region

Climate change can cause many negative impacts including more droughts and wind throw events, ice storms, increased fire hazards, increased pest infestation and weed invasion, finally leading to reduced forest outputs (Williams & Liebhold, 2002; Irland, 2000). There is already a large body of evidence presented in published reports that climate change has negatively affected forest ecosystems, causing decline in tree growth and dieback, invasive species problems, species distributions and migrations, seasonal patterns in ecosystem processes, demographics and even extinctions (IPCC, 2007). Table 1.6 summarizes recent changes, future scenarios and potential impacts of climate change in each region.

Table 1.5 Examples of current forest policy objectives in the Asia-Pacific region (adapted from Yasmi et al. 2010)

Country	Current policy objectives	Remarks
China	• Improve biodiversity conservation and secure adequate national ecological management • Restore key ecosystems • Promote sustainable forest management (SFM) • Clarify forest land tenure and farmers' rights and responsibilities vis-à-vis forest and forest land management • Promote forest industries • Strengthen international cooperation	Forest policies in China show a clear shift from primarily timber production to SFM in recent decades.
India	• Maintenance of environmental stability, restoration of ecological balance and soil and water conservation • Meeting the needs of local communities through partnerships between forest departments and local communities • Achieve a target of 33% of national land area under tree cover • Promote partnerships between industries and farmers to produce raw materials	Forest policies have shifted radically from regulatory to participatory management embracing SFM objectives
Myanmar	• Protection of soil, water, wildlife, biodiversity and environment • Sustainability of forest resources • Support basic needs of people • Harness economic benefits • Participation of people • Public awareness of the vital role of the forests in the well-being and socio-economic development of the nation	Forest policies embody the broader concept of SFM, biodiversity conservation and public participation – both forest and people-focused
PNG	• Commercial logging based on SFM principles • Conserving natural forest for the benefit of people	SFM objectives are used as guiding principles

Table 1.6 The recent changes, future scenarios and impacts of climate change

	Asia	Australia and New Zealand	Pacific
Recent Changes	Surface temperature: rose 1- 3 °C over a century; Longer heat waves; Precipitation: increased intense rainfall events; decreased total rainfall amount. Extreme events: increased frequency and intensity (tropical cyclones, droughts, etc.). Sea-level: rose 1-3 ml/year.	Surface temperature: rose 0.4 – 0.7 °C since 1950; more heat waves (northwest Australia and southwest New Zealand); hotter droughts. Precipitation: more rainfall in northwest Australia and southwest New Zealand; less rainfall in southern and eastern Australia and north eastern New Zealand. Extreme events: increased extreme rainfall events in north western and central Australia; decreased in the southeast, southwest and central east coast.	Surface temperature: increased faster than 0.6 °C in twentieth century; Increased number of hot days and warm night in the South Pacific. Sea-level: rose about 2 ml/year. Extreme events: increased frequency and intensity of tropical cyclones originated in the Pacific.
Future Scenarios	Increasing extreme events (heat waves and intense rainfall) in South Asia, East Asia and Southeast Asia; sea surface temperature will rise 2 – 4 °C; increasing intensity of tropical cyclones.	Increasing frequency of heavy rainfall events; temperature will rise about 0.1 – 1.3 °C by 2020 within 800 kilometres of Australian coast; 0.1 – 1.4 °C by 2030s in New Zealand; sea-level will rise 0.18 – 0.59 meters by 2100 (±25 percent modification).	Surface temperature will rise greater than 2.5 °C in South Pacific.
Potential Impacts	Rising risk of species extinction; increasing coastal erosion and floods.	Declining productivity of forests.	More frequent and intense floods, storm surge and coastal erosion.

Forest management for climate change adaptation

Adaptation needs in the Asia- Pacific region

The adaptation needs provided below are based on IUFRO's global assessment report on forest and human adaptation to climate change (Seppälä et al. 2009).

1. Combine traditional forest-related knowledge and formal forest science

Traditional forest-related knowledge (TFRK), practices, and institutions have developed over generations by forest-dependent people. Traditional forest and water management practices are very important to climate change adaptation. Expanding markets have weakened of traditional cultures and TFRK. TFRK should be recorded, translated and synergized with formal forest science, before it is lost.

2. Increase participatory reform and flexibility in forest-related bureaucracies

Standard operating procedures in forest bureaucracies need to change. Locatelli et al. (2008) stress two key changes that are required:

- Forest-dependent people need to be recognized, to be drawn into the discourse and to contribute to official decision-making.
- Changing attitudes among forestry personnel and strengthening feedback mechanisms within forestry-related bureaucracies.

3. Maintain/enhance biodiversity as a key ecosystem service

Management for maintaining biodiversity includes the prevention of disturbances such as fire (managing fuel load, prescribed burning) and maintaining natural cycles, particularly in arid and semi-arid forest areas. The prevention of invasive species and diseases is also crucial for maintaining biodiversity, through quarantine regimes and phytosanitary procedures. Another option is to assist forests to adapt after a perturbation by establishing priority species according to planned ecological succession (Locatelli et al. 2008).

Increasing landscape connectivity through the establishment and preservation of corridors and reducing forest fragmentation is important to facilitate natural progression and succession within ecosystems. Connectivity and corridors increase the ability of species to adapt through migration and the maintenance of genetic diversity.

In managed natural forests, for example, logging gaps may be planted with a variety of seedlings to maximize genetic diversity. Tree plantations may be established with a range of genotypes, seed sources and age classes to increase their capacity to adapt to expected future climate conditions. Plantation management strategies that mimic natural conditions and avoid monocultures are advocated to take into account climate change adaptation requirements (Roberts 2009). Throughout the region, traditional home gardens have included drought-resistant fruit trees to provide a source of livelihoods during drought years when other crops fail (Boven and Morohashi 2002).

4. Create/enhance robust management strategies and extensive communication networks

Because of the uncertainty of impacts of climate change, robust, sustainable forest management strategies are needed. Community-based management strategies are an important tool for ensuring responsiveness. These management strategies must also consider the projected increase of forest disturbance regimes in the form of fire, pests and diseases and must be flexible enough to incorporate and respond to new information. Effective adaptation requires the formation of extensive communication networks for monitoring the effectiveness of strategies at local, national and regional levels.

5. Improve inter-sectoral coordination

Policies from agriculture, transportation and land-use sectors will exert significant influence on the forest sector. Forest adaptation should not ignore the many anthropogenic drivers of forest change that originate in other sectors; developments in agriculture, energy, transportation, conservation and macroeconomic policies can have dramatic effects on the incentives to destroy or degrade forests.

6. Mainstream forest adaptation into policy

In order to mainstream forest-based climate change adaptation strategies at the country level, National Forest Programmes (NFPs) must explicitly address both the role of forests for reducing vulnerability to climate change at the national level and the importance of increasing the adaptive capacity of forests themselves.

7. Incorporate new actors and new modes of governance

Many institutions and sectors are becoming increasingly concerned about forest-based climate change adaptation strategies from the local to the global scale. They include local forest-dependent communities, commercial or industrial forest stakeholders, ecotourism ventures, conservation and development NGOs, national agencies concerned with forests, power generation agencies and industries, agriculture and food sectors, disaster risk reduction organizations, intergovernmental organizations, international research/development organizations and funding agencies. Adaptation policies should aim at linking these diverse actors with those engaged in forest conservation and management.

Adaptive forest management

Adaptive forest management for climate change is consistent with SFM (IUFRO 2009). Adaptive management involves design, management and monitoring processes and requires constant learning from the past to plan for the future (FAO 2010c).

The major goal of adaptive management is to enhance ecosystem resiliency to disturbances by releasing stresses so that forests can survive under a changing climate (Salafsky et al. 2001). Biodiversity conservation is an important measure to achieve this goal because more diverse ecosystem tends to be more resilient to disturbance events such as insect outbreak. Tree species should be conserved with dispersed and viable populations in order to reduce the risk of extinction (Fischlin et al. 2007). Planting forests with mixed species rather than single species can also leads to higher biodiversity in the ecosystem (Spittlehouse & Stewart 2003).

Other adaptation strategies and practices include: changing rotation periods, salvaging dead timber, shifting to species more productive in altered climatic conditions, taking action to minimize fire and pest damage, connecting corridors and adjusting production objectives to altered wood size and quality (Spittlehouse and Stewart 2003), reducing damage to remaining trees, practicing reduced-impact logging, and employing soil conservation.

From the administrative point of view, forest managers should be allowed "freedom to fail" within an allowable extent when implementing their forest practices, because it is difficult to achieve goals in a first trial given variable environmental factors (Locatelli et al., 2008). Although there are models that can be used to predict the impacts of climate change, results are often limited to a general trend rather than detailed impacts (FAO 2010c). Therefore, forest management strategies need to be robust and diverse considering such uncertainty and the increasing disturbances under climate change. Community-based management can help to ensure the responsiveness of management plans, while monitoring can help to secure the activeness (FAO 2010c).

For example in Nepal and many Indian states, local communities have sole control over forest management and the power in policy-making process. Community-based management has resulted in more efficient feedback from the direct stakeholders in the community and has also led to improved policies benefited from field experience (Poffenberger 2000).

Estimation of adaptation costs

Adapting to climate change involves a significant transition with far-reaching economic implications. Full economic assessments of the costs associated with adaptation allow countries to prioritize strategic measures and anticipate the associated development impacts. To date, knowledge on anticipated adaptation costs, particularly those costs specific to the forestry sector, remains highly limited and imprecise.

Since 2006, there have been only five global studies estimating climate change adaptation costs for developing countries. The estimated cost is summarized in Table 1.7.

Table 1.7 Estimate of adaptation cost (FAO (2010c))

Estimate year	Estimate by	Cost (US billon/annually)
2006	World Bank	9-41
2006	Stern Review	4-37
2007	Oxfam	50
2007	UNDP	86-109
2007	UNFCCC	27-66

Mitigation options and issues

1. Reduced emissions from deforestation

Between 1850 and 1995, 75 percent of the total carbon emissions in South and Southeast Asia were due to the clearing of forests for permanent crops. This trend is set to continue, even though deforestation rates in tropical Asia have declined since the 1990s (Houghton and Hackler 1999).

Strategies for avoiding deforestation depend upon the drivers of deforestation in each context. However, there appear to be four clear categories of mitigation strategies for avoiding deforestation (see Peskett and Harkin 2007):

- Strengthening existing policy and legislation for forest protection.
- Reclassification of land-use zones or renegotiating concessions.
- Modification of agriculture or infrastructure programmes to reduce pressure on forests.
- Implementation of economic incentives through PES, or disincentives such as taxes or fines.

2. Enhanced carbon sequestration from afforestation, reforestation and other strategies

There is a suite of strategies to create carbon sinks through forestry. Some of these strategies are:

- Afforestation: Establishment of planted forests on lands that historically have not been forested
- Reforestation: Planting of new forests on land that had tree cover recently
- Forest restoration: Restoring degraded forests through assisted or natural regeneration; protecting secondary and other degraded forests to allow them to regenerate naturally; or mechanical/ infrastructural means, such as damming canals that drain peatlands.
- Modification of forest management practices to increase sequestration: Including prevention of fires, changing harvesting rotations and practices (e.g. reduced impact logging).
- Adoption of agroforestry practices: Increasing tree cover on agricultural or pasture lands.
- Urban forestry: Planting trees in ‘vacant areas’ for urban green space.
- Increasing soil carbon: Soil restoration and woodland regeneration, no-till farming, introduction of cover crops and set-asides (Lal 2004).

3. Conservation of natural forests

The majority of forest cover in the Asia-Pacific region is natural (79 percent) (Houghton 2005). However, most reported gains in forest area and condition in the region are confined to planted forests. The natural forest area decreased at a rate of 0.48 percent per year during the 1990s and by 0.50 percent per year during the 2000s, while planted forest area increased at annual rates of 2.02 percent and 2.85 percent during 1990-2000 and 2000-2010 respectively (FAO 2010c). Conservation of natural forest resources is therefore a critical component of climate change mitigation strategies in the region. Furthermore, natural forests should be of high priority because they contain more biomass than plantations or agroforestry systems: that is, natural forests contain 250 tC/hectare versus 90-120 tC/hectare and 50 tC/hectare for agroforestry systems and plantations, respectively (Pagiola and Bosquet 2009).

4. Reduced emissions from forest degradation

Forest degradation that leads to carbon emissions in the region is significant, especially in South and Southeast Asia. Degradation results from human activities such as shifting cultivation, logging, grazing and fuelwood extraction, as well as natural causes such as forest fires and pests or diseases (Houghton and Hackler 1999, Griscom et al. 2009). Degradation can be reduced through improved forest management practices such as: fire and pest control; adoption of reduced impact logging; reduction of fuelwood collection, grazing management, etc. It is vital that degradation be addressed, not only for its impact on emissions but also for its capacity as precursor to or catalyst of deforestation (Streck et al. 2009).

5. Substitution of harvested wood products for other materials and of wood fuels for fossil fuels

Biomass energy can be used to replace fossil fuels, thereby reducing GHG emissions from fossil fuel. The avoided emissions of a biomass energy system are equal to the fossil fuels replaced minus the emissions resulting from the biomass energy system (IPCC 2000). Under such a system, fuelwood production must be carefully managed so that forests maintain a constant carbon stock. There are two main approaches to fuelwood production: sustainable harvesting of fuelwood from natural forests and commercial harvesting from intensively managed plantations. Both approaches may play a role in increasing substitution of fossil fuels with renewable fuelwood.

In addition to wood fuel, other kinds of biofuels are also being utilized to replace fossil fuels. These include palm oil (for biodiesel), sugar cane (for ethanol production), Jatropha curcas (biodiesel) and other crops including canola (rapeseed) and sugar beet. Emission reduction outcomes from burning biofuels are mixed, depending upon the yield of fuel as a percentage of raw product, their efficiency as fuels and the conditions under which they are produced and delivered from producer to consumer. For example, clearing land to make way for oil-palm plantations, especially on peat soils, can result in huge emissions that far exceed any gains from consumption of the resulting biofuel. Alternatively, biofuels that make use of waste biomass grown on degraded lands offer immediate, sustainable emissions reductions (Fargione et al. 2008).

Finally, using wood products to replace other materials in furniture and construction may enable carbon sequestration, although it is unclear whether this will achieve emissions reductions. Other non-wood products like bamboo and rattan also sequester carbon and may offer greater potential (FAO 2009a).

Adaptation-mitigation synergies and trade-offs

Adaptation is defined as “adjustment in natural or human systems in response to natural or expected climatic stimuli, or the efforts which moderate harm or exploit beneficial opportunities”. Mitigation is defined as “any anthropogenic intervention to reduce sources or enhance the sinks of GHGs". This has resulted in mitigation and adaptation being distinguished in spatial, temporal and socio-economic terms. Mitigation has been associated with globally-coordinated efforts with a focus on long-term implications, the burden of which lies upon developed nations. Adaptation, on the other hand, concerns the immediate need for vulnerability reduction at the local level, the burden of which will mainly fall on developing and least developed nations which are least able to cope (Ayers and Huq 2009).

Synergies between adaptation and mitigation measures have recently been explored in developing countries within the Asia-Pacific region aiming to identify win-win options for climate change policy and seeking opportunities to explicitly include adaptation objectives in mitigation projects (Klein et al. 2007, Wilbanks et al. 2007). Venema and Rehman (2007) argue that synergy between mitigation and adaptation is intrinsic to the ecosystem-oriented approach articulated by the World Summit on Sustainable Development.

Synergies are most clearly evident in the LULUCF sector. Forestry, in particular, is relevant to climate change adaptation strategies, with its contribution to biodiversity conservation and livelihood resilience, and to mitigation through enhanced CO_2 sequestration (Ravindranath 2007). Agroforestry offers the highest potential for carbon sequestration among land uses identified by the IPCC, owing to the large area currently devoted or potentially available for such use. The conversion of row crops or pasture into agroforestry systems can greatly enhance stored carbon above and below ground as well as increase farmers' economic benefit (Verchot et al. 2007).

Verchot et al. (2007) contains numerous references to community-based approaches to forest management. It is therefore no surprise to learn that some of the clearest practical linkages between adaptation and mitigation strategies have emerged in the field of community forestry. For example, since 2008, FAO has been supporting Nepal's National Agricultural Research Council and other government bodies in a climate risk management project. A key element of the project's strategy is to explore synergy between the economic resilience and adaptive capacity that CFUGs confer on their members and their potential to contribute successfully to forest-based mitigation strategies under REDD (FAO 2009b). Many others have noted this synergy in South Asia (Karky 2009, Ravindranath 2007) and a common understanding of community forestry both as an element of REDD methodology and a local-level adaptation strategy is taking root in the region. Another adaptation policy that improves carbon sequestration is the protection and improved management of ecosystems that serve as buffers against extreme weather events, particularly coastal habitats such as wetlands and mangrove forests (World Bank 2009).

REDD is a clear example of a strategy to address climate change which combines mitigation and adaptation elements. So, although synergies do indeed exist with win-win outcomes, even these require optimal mixes of adaptation and mitigation elements. Trade-offs exist between these two sets of objectives based on a number of complex factors, such as the exhaustibility of forest resources and the conflicting needs and interests of stakeholders (Dang et al. 2003). There are also a number of instances of conflicting approaches to adaptation and mitigation. Many adaptation options, such as improved flood defences, are known to increase energy use, hence interfering with GHG reduction efforts. Relocation of vulnerable communities, for example from low-lying coastal zones in the Mekong Delta, to currently forested areas further inland, is a central feature of Viet Nam’s National Target Plan for Climate Change Adaptation. These plans, if followed through, will conflict directly with the country’s strategy to implement REDD nationwide.

The IPCC concludes that there is insufficient information to ascertain whether investment in adaptation could, in effect, buy the time required for mitigation efforts to deliver results, nor what level of investment would be required to achieve this on the global scale (Klein et al. 2007). However, Dang et al. (2003) argue that it is possible to set a national climate policy that takes into account the synergies and trade-offs between adaptation and mitigation. A proper national framework for integrating adaptation and mitigation strategies for ecosystems, resources and sectors should be the first priority for climate change policy-makers.

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Chapter 2. Tools to Aid in Sustainable Forest Management

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Introduction

We live in a complex natural environment, where physical, chemical and biological processes are going on spatially and temporally. To understand certain phenomenon, predict the complexity of these processes and obtain essential information for the development of our society, we have to establish and use models. A number of models and tools exist which can be used to aid forest management under a changing climate. A model is a simplified substitute of the real world, such as a geographical map, a globe, a city plan, a mathematic equation to describe forest stand grow and yield or a river flow during different time intervals (daily, monthly or annually) are all models. Ljung and Glad (1994) defined that a model is a tool used to answer questions about a system without having to do an experiment. A model can be a physical one, such as a globe, a geographical map and the miniature of a river used by hydrologist to test hydrological properties.

A model is applied when a substitute is easier to analyze than the reality. It is an abstraction and simplification of the real system, but it does comprise all the characteristic ones, those essential to the problem to be solved or described (Soetaert and Herman 2009). A model can help you test your idea and solution quickly and cheaply. In general, a model can be used:

- To analyze the evolving behaviors of a system,
- To find interrelationships between different elements in the system,
- To forecast the future behaviors of the system,
- To assess the risks and uncertainty of the system,
- To evaluate policies on the system,
- To help for new policy, plan and strategy making.

With reference to forest management, models can help us answer following like questions:

- What will the forest look like in terms of yield, carbon, water control and other ecosystem services without social and natural disturbances?
- What might these services change with socio-economic activities and natural disturbances?
- What might they behave under different scenarios of climate change?
- Are the current socio-economic activities and management policies sustainable? and
- Can the current policies adapted to the climate changes?
- If not, how to change our socio-economic activities, and what policies and strategies should we adopt to meet the climate changes?

- Is there any risk and uncertainty in future scenarios and these strategies?
- What should we do?

Modelling Process

The modelling process can be illustrated by Figure 2.1.

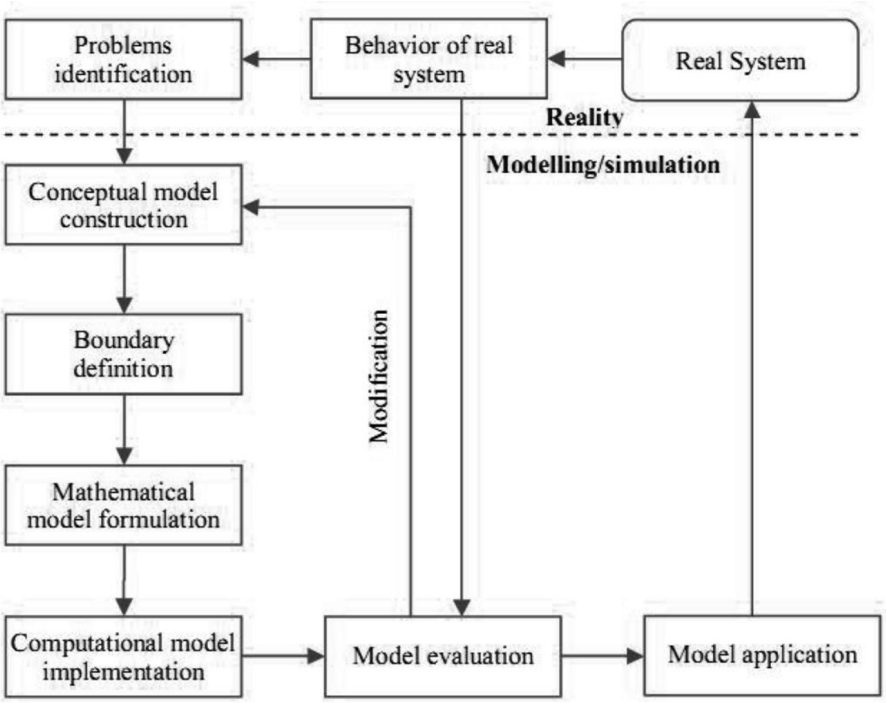

Figure 2.1 A sketch of modelling process

Modelling starts with observing a system through collecting data by measuring and/or doing experiments and analyzing the data. It is not difficult to build a model after collecting required data. The difficulty of modelling is to make the model reliable and accurate, i.e. calibrating and validating the model. Only the results of a well calibrated and validated model are helpful for us. The verification techniques include having the model structure and code checked by an expert, checking logic of the model flow, and examining reasonableness of the model outputs. In most case modelling inputs lack certainty due to many reasons, such as limited knowledge on the modeled system, mistakes of measurements, changes of driving forces, and whatever. Input uncertainty will result in modelling outputs uncertainty. Sensitivity analysis is the study of the uncertainties where how the variations of input changes influence outputs. It is very helpful to test the robustness of the model results, further understand the relationships between model inputs and outputs, identify the “high-leverage” and “low-leverage” variables, and increase awareness to reduce the uncertainty.

Mathematical Models

Here we are concerned exclusively with mathematical models, which mimic reality by using the language of mathematics (Bender, 1978). Mathematical models take many forms, a number of which three are summarized here.

A **statistical model** is a formalization of relationships between variables in the form of mathematical equations, which describes how one or more random variables are related to one or more other variables. The model is statistical as the variables are not deterministically but stochastically related. Regression models are simple but widely used. For example, grow models of Chinese Fir in terms of *Height* (H) and *Diameter at Breast Height* (DBH) can be expressed by the following mathematical equation (Figure 2.2):

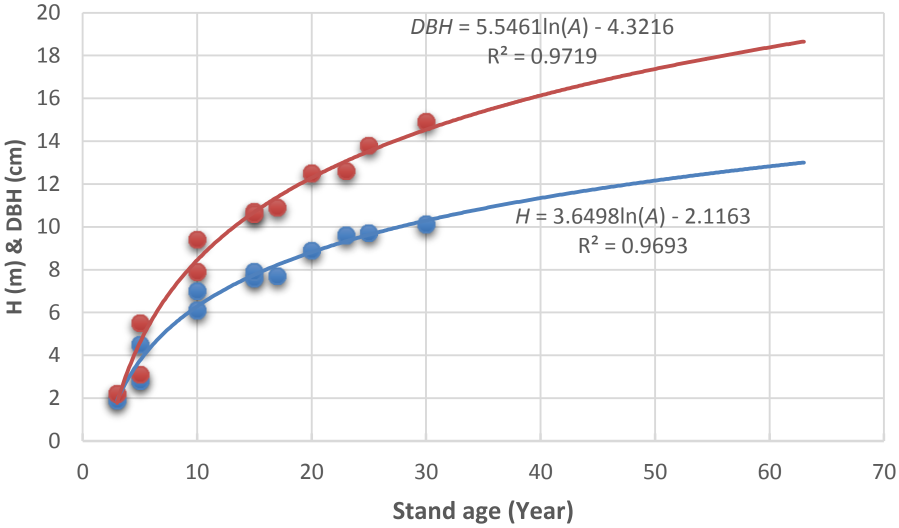

Figure 2.2 A grow model of Chinese Fir in terms of Age and DBH

Optimization or programming models are models used to find the best possible solution from a set of possible alternatives based on series of conditions or criteria. An optimization problem usually comprises maximization or minimizing of one or more objective function within some constrains.

As an example, an optimization model taken from Abdullah et al. (2009) used to optimize the total harvest volume is expressed as:

$$\max Q = \sum_t \sum_i HV_{it} \tag{1}$$

$$s.t. \quad TD_{it} \geq RTD \quad \forall_{it} \tag{2}$$

$$\sum_i PVB_{it} \geq RVB \quad \forall_t \tag{3}$$

$$VB_{it} \geq RVB \quad \forall_{it} \tag{4}$$

$$\sum_i HV_{it} \geq AVP \quad \forall_t \tag{5}$$

where *i* is harvest block, *t* is planning period, *TD* is tree diameter, *PVB* is potential harvest volume in each block, *VB* is volume harvested in each block, *HV* is harvest volume, *RTD* is required tree diameter restriction, *RVB* is required volume harvested in each block, *AVP* is allowable volume harvested in each planning period.

The objective of these types of models is to maximize the objective function (*Q*), i.e. the total harvest volume in each planning period with set of constraints, where constraint (2) limits the minimum tree diameter for harvesting in each block, constraint (3) is the restriction of total potential harvest volume in each block, and constraints (4) and (5) provide limitations of harvest area.

Dynamic system models is a theory of system structure and an approach for representing such a complex system and analyzing its dynamic behavior (Forester 1961). Comparing to the traditional methods, the SD simulation approach studies the dynamic, evolving, cause-effect interrelations, and information feedbacks that direct interactions in a system over time, and it does not require longitudinal (Panel and Time Series Cross-Section) data. SD is usually characterized as a ‘‘strategy and policy laboratory’’ and ‘‘socioeconomic system laboratory’’ because it provides a tool to test the effects of various strategies and policies in a system, especially for socio-economic systems. The SD simulation model consists of a set of nonlinear differential equations, such as level (or state) equations, flow equations, auxiliary equations, parameter equations, condition equations as well as initial value equations. As an example, the following shows a simplified volume stock SD model framework to illustrate the SD modelling concept (Figure 2.3). To study system dynamic modelling approach, please refer to (Wei et al. 2012a; Mendoza and Prabhu 2006; Purnomo and Mendoza 2011; Deaton and Winebrake 2000).

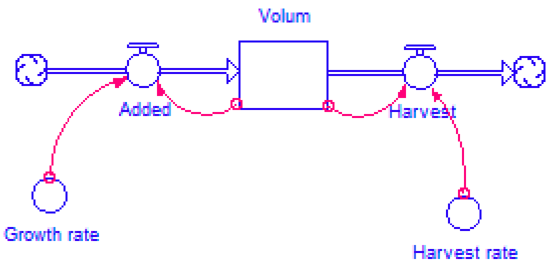

Figure 2.3 A simplified forest volume stock SD model

Six Models and Their Applications

Six modelling tools are highlighted, and example applications provided in the proceeding chapters, in this manual.

Conventional Forest inventory and Growth and Yield Models

A forest inventory is a description of the kind and quantity of forest resources and the location of these resources. Included in the inventory are maps of the resources to show locations, and data files and summaries containing area measurements, tree and stand attribute data, wildlife counts and other information. Thus the information in a forest inventory is critical for making good resource management decisions. In the past, forest inventory information was maintained using paper files and maps. Information was retrieved by hand and information on several forest resources (e.g., water with timber) was obtained by physically overlaying the corresponding maps and combining the data. With the advent of computers, data files and summaries were stored on magnetic disks and tapes; retrieving data or combining data from several resources was achieved by using computer programs. However, retrieval or combining of map information was difficult. If a resource manager, such as a forester or wildlife biologist, wished to know where a particular type of forest (e.g., old growth Douglas-fir stands) was located, the maps of the area were retrieved and appropriate areas were colored to show the areas of interest. Geographic information systems (commonly called GISs) were developed to computerize map information (spatial data), and combine the map information with the resource data (attribute data).Once the spatial and attribute information is loaded into the GIS, retrieval of information for one or more forest resources became considerably quicker.

Forest inventories provide base information for all planning and management activities at all spatial scales from the world to a local area, and all time scales from historical to 100 year or longer projections forward in time. The need for current, accurate, and accessible forest inventory data has increased with increasing competition for resources, changes in climate, and greater global interaction and communication. Unlike many other countries, population pressures are localized in Canada. Nevertheless, land use competition has increased with increased world demand for timber products, fossil fuels, minerals, and water. For some areas of BC, forests are being converted to urban areas. In other areas, most recently in northeastern BC, oil exploration has resulted in extensive forest removal and/or pressure to increase forest removal. Increased use of forest land has resulted in more rapid and extensive changes, emphasizing the need for current and accurate forest inventory information. At the same time, changes in climate are affecting natural disturbances, particularly fire, pests and disease in BC, requiring both current and future forest inventory information[1].

Growth and yield models derived from forest inventory data also provide critical information for forest management decisions. They are the production functions that support all timber management as well as other values that depend on the characteristics of the trees in a forest. In forest management the objectives often are achieved by controlling the characteristics of a

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[1] Excerpts from: Moss, I., P.L. Marshall, and V.M. LeMay. 2006. Assessment of the status of natural resource inventories in British Columbia: Background report. November 22, 2006. Prepared for the Association of BC Forest Professionals.

forest stand or set of forest stands in order to influence the growth and yield of those stands. Thus, it is important to introduce key stand characteristics that most affect growth and yield. A growth and yield model should incorporate and predict the relationships between the characteristics of a stand and the growth and yield of the timber in the stand. Some conventional growth and yield models using an inventory are presented in Chapter 3.

Climate Extrapolation and Future Scenarios Models

With a rapidly growing number of climate change related studies and applications, the demand for high-resolution and high-quality spatial climate data is high. Historical climate data are necessary for understanding the relationships between climate variables and plant performance including their health and productivity. They are also essential for modelling the climate niches and distributions of ecosystems and their components. After such relationships or models have been built, future climate projections are needed for projections of the impact of climate change on the subjects under concern. Future projections can then be used as scientific basis for developing adaptive strategies. For these objectives, climate data are required to represent the climate conditions as close as possible to the truly climate conditions where the ecosystems or plants reside.

The climate data from weather stations are the most accurate and reliable. However, as the number of weather stations is limited, the locations of our interests are usually far away and have considerably different climate conditions from weather stations. Therefore, interpolation techniques are often used to predict climate conditions for these locations or for developing spatial climate datasets to cover a certain area. Statistical methodologies applied to interpolate climate data are mostly based on distances from nearby weather stations, such as Kriging, bilinear and spline interpolations. Due to the complexity in topography and other factors affecting the climate, the reliability of the interpolated climate data is often not accurate enough.

The ANUSPLIN software developed by at the Australian National University using thin plate smoothing splines improves the interpolation, and it has been widely used. WorldClim generated grid climate data for the entire globe using this approach (Hijmans et al. 2005). However, ANUSPLIN is still a purely statistical based approach and accuracy is limited for the area with complex topography. Another widely used interpolation method is Parameter-elevation Regressions on Independent Slopes Model (PRISM) (Daly et al. 2002) developed at the Oregon State University. PRSIM uses a combination of statistical approach and expert knowledge based adjustment considering rain shadows, coastal effects, and temperature inversions. PRISM climate data are regarded as the highest-quality spatial climate data sets currently available. Interpolated climate data are available for the United States and some other regions including China.

The availability of climate data is improving with time. However, some challenges exist for non-meteorological users. ClimateAp is developing to tackle the challenges and to provide an essential tool that is all-in-one package and easy to use for non-meteorological users (See Chapter 4 for detail).

Carbon Balance Modelling

Forest managers, policy-makers, and governments require the means to quantify past forest C stocks and stock changes, and to explore future forest and land-use policy options. Tools developed to meet these needs typically involve a significant modelling component for generating estimates of C stocks and stock changes for large landscapes, as it would not be cost-effective to obtain these through measurements alone. Modelling is also the only means available to simulate future conditions. Forest ecosystems are heterogeneous, so there will never be enough field measurements to characterize all forests under all conditions (Running et al. 1999). Models of forest C dynamics are usually grouped into those where growth is driven by empirical yield curves (e.g. EFISCEN, Nabuurs et al. 2000; CO2FIX, Masera et al. 2003) and those where growth is driven by simulating photosynthesis (e.g. 3-PG, Landsberg and Waring, 1997; BIOME-BGC, Running and Gower, 1991; CENTURY, Metherall et al., 1993; TEM, Tian et al., 1999). Both types of models are valuable for different applications. Empirical yield data driven models are powered by the same data that operational foresters use in timber supply analysis and forest management planning tools. These models require data on merchantable wood volume as a function of stand type and age. An application that yield-driven models are particularly well suited for is the explicit simulation of human activities and natural disturbances. The empirical model, Carbon Budget Model-Canadian Forest Sector 3 (CBM-CFS3), detailed Kurz et al. (2009) summarizes the key components of CBM and its application in quantifying British Columbia pilot site carbon budgets and accounting. A brief description of CBM-CFS3 is presented in Chapter 5.

Forest Landscape Models of Succession, Disturbance and Climate Change

Forest landscape models have been evolved over last decades. Traditional non-spatial stand level growth and yield models couldn't address some ecological science and management questions (Mladenoff 2004). LANDIS (Landscape, Disturbance and Succession) is one of landscape models that was developed in the early 1990s for use in the forests on Wisconsin and Minnesota, since then it has been used all over North America and in Europe, China and recently in Australia and has subsequently between improved and expanded upon resulting in the development of LANDIS-II (Mladenoff 2004). LANDIS-II is a forest landscape simulation model that simulates how ecological processes including succession, seed dispersal, disturbances, and climate change affect a forested landscape over time and space. Some processes in the model are always active, succession for example, while other processes such as disturbances and management are optional (Scheller and Domingo 2011). A brief description of LANDIS-II is presented in Chapter 6.

Climate Niche Modelling for Ecosystems and Species

Climate is the primary factor regulating the geographic distributions of forest ecosystems and tree species (Woodward 1987, McKenney et al. 2007). A forest ecosystem or a tree species is adapted to a range of climatic conditions, which is often referred to as "climatic niche" (Figure 2.4A). The original definition (Hutchinson 1957) of niche is the set of biotic and abiotic conditions in which a species is able to persist and maintain stable population sizes. The **fundamental niche** describes the abiotic conditions in which a species is able to persist, whereas the **realized niche** describes the conditions in which a species persists given the presence of other species (e.g., competitors and predators). The climatic niche is the climatic factor of the abiotic conditions. Climate niche is also called climate envelope (fundamental niche) or bioclimate envelope (realized niche).

The climatic niche of a tree species is unlikely to change (Peterson et al. 1999), at least not in short-term (Ackerly 2003, Wiens and Graham 2005). If climate change continues, the geographical distribution of the climatic niche for the species will shift. In fact, such shifts have already been observed in a large number of plant and animal species (Parmesan and Yohe 2003, Parmesan 2006).

For long-lived tree species, because of their slow rates of migration, climate change will likely result in a mismatch between the climate that trees are currently adapted to and the climate that trees will experience in the future (Aitken et al. 2008) (Figure 2.4B). Individuals or populations exposed to climate conditions outside their climatic niches will be maladapted, resulting in compromised productivity and increased vulnerability to disturbance. Therefore, efforts to model the climatic niche of forest tree species and associate forest ecosystems, and to project their shifts under future climates, have proliferated in recent years. Projections of shifts in tree species distributions can be achieved with niche-based bioclimate envelope models or process-based mechanistic models. Due to limited knowledge on the bio-physiological processes of tree species and the computational complexity, bioclimatic envelope models (i.e., also referred to as "ecological niche models") have been used more widely (Pearson et al. 2006, Rehfeldt et al. 2012, Wang et al. 2012a).

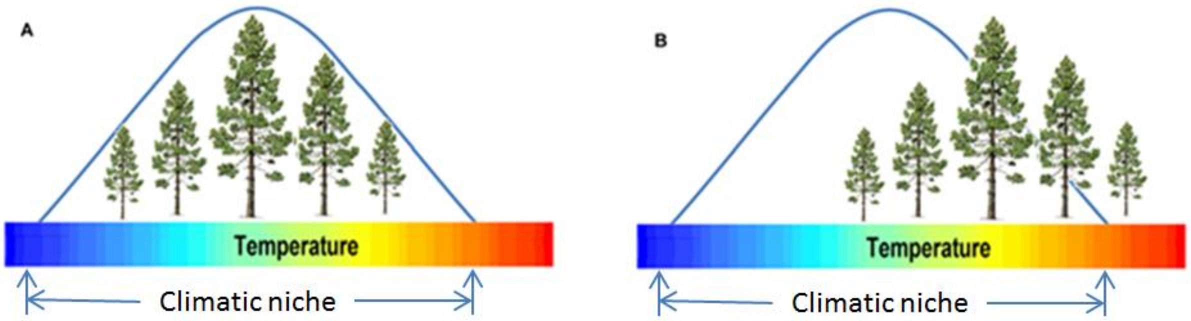

Figure 2.4 Illustration of climatic niche for a tree species for current (a) and future (b) climates.

Bioclimate envelope models are built based on the relationships between observed presences of a species and values of climate variables at those sites. Thus, these models require present-absent data, showing where the trees grow and where they don't and high-resolution climate data that reflect climatic conditions where the species is present or absent. A powerful modelling approach can effectively capture the relationship between the species occurrence and climate variables. Because Bioclimate envelope models rely on actual distribution of the target species, they model the realized niche as opposed to the fundamental niche. However, it is important to emphasize that these models predict the shift in distribution of the climate niche of a species rather than the shift in distribution of the species *per se*. The fate of any tree species will depend on genetic variation, phenotypic variation, fecundity and dispersal mechanisms, and their resilience to a multitude of disturbances.

Climate envelope models of ecosystem change have been criticized for their failure to account for species migration capacity, changes in species interactions, and alterations to biogeochemical cycles, including increased atmospheric CO_2 concentrations (Pearson and Dawson 2003, Araujo and Guisan 2006, Austin 2007, Botkin et al. 2007, Thuiller et al. 2008). However, bioclimatic envelope models do accurately predict realized climatic niche or bioclimatic envelope of an ecosystem or a species, which are the target of many ecosystem management activities. As Rehfeldt et al. (2012) recently suggest, the assumption of stable species interactions in ecosystem climate envelope models is only invalidated under novel future climates and robust methods for incorporating biogeochemical processes are not yet well-developed for either climate envelope or mechanistic modelling approaches. We believe that when the results of climate envelope model projections are appropriately conveyed and used with their limitations in mind, they can provide a powerful framework for evaluating and illustrating potential climate change impacts and guiding land-use planning.

Although bioclimatic envelope models have been widely used, challenges arising from model accuracy and the uncertainty of future climates make it difficult to apply the model projections with confidence in developing adaptive strategies in natural resource management. These challenges will be addressed in Chapter 7.

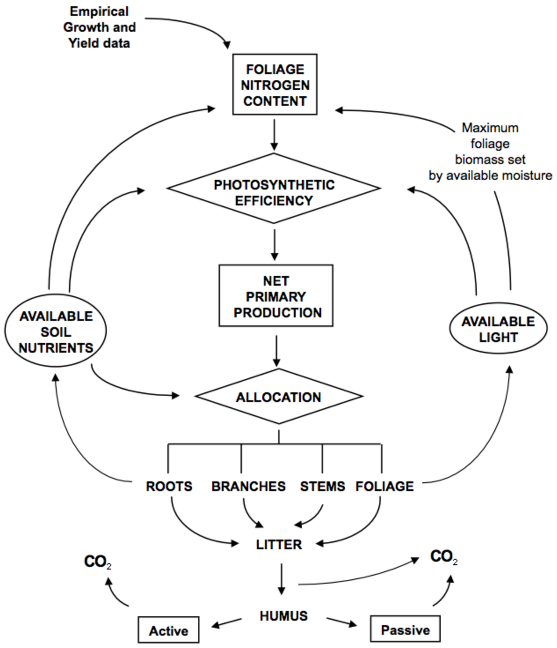

Figure 2.5 A schematic illustration of the key ecosystem processes and flows represented in FORECAST.

Modelling Climate Impacts on Forest Growth and Mortality

FORECAST Climate is an extension of the FORECAST model (Kimmins et al. 1999), a management-oriented, stand-level forest growth simulator. FORECAST has been under development and application for more than four decades and its output has been evaluated against field data for growth, yield, ecophysiological and soil variables (Bi et al. 2007, Blanco et al. 2007, Seely et al. 2008). FORECAST employs a hybrid approach whereby local growth and yield data are used to derive estimates of the rates of key ecosystem processes related to the productivity and resource requirements of selected species. This information is combined with data describing rates of decomposition, nutrient cycling, light competition, and other ecosystem properties to simulate forest growth under changing management conditions (Figure 2.5).

Decomposition and dead organic matter dynamics are simulated using a method in which specific biomass components are transferred, at the time of litterfall, to one of a series of independent litter types. Decomposition rates used for the main litter types represented in the model are based on the results of extensive field incubation experiments (Camiré et al. 2002, Prescott et al. 2000, Trofymow et al. 2002). Residual litter mass and associated nutrient content is transferred to active and passive humus pools at the end of the litter decomposition period (when mass remaining is approximately 15% to 20% of original litter mass). Mean residence times for active and passive humus types are typically in the range of 50 and 600 years, respectively. Modifications to the various processes represented within FORECAST due to the influence of climate are described in Chapter 8.

Regeneration Models

Individual species modelling is typically done using one of two techniques: Statistical modelling or mechanistic modelling. Statistical modelling typically takes the form of bioclimatic envelope models (also known as species distribution models (SDM)) which typically assume that species are at equilibrium with climate and do not consider biotic and abiotic factors. These approaches generally reflect the ecological niche (i.e. realised niche) of a species to their correlative nature and therefore typically provide no explanation of the physiological mechanisms that may drive species occurrence and change at finer spatial scales. SDMs are also regarded as poor predictors of species dynamics under changing environmental conditions; however, these models can be useful for modelling species responses at coarse scales, typically where patterns are driven by climatic factors, but at finer scales these patterns are driven by the distribution of resources and phenology. Mechanistic modelling can bridge this gap by providing an explanation of the mechanisms that may drive change resulting in more accurate predictions of species response to environmental change (Guisan and Zimmerman 2000). The Tree and Climate Assessment model (TACA) (Nitschke and Innes 2008, Nitschke et al. 2012, Mok et al. 2012) is a mechanistic species distribution model that focuses on modelling the response of tree species to changes in climate and soil moisture within their regeneration niche. The model has two variants TACA-EM and TACA-GEM, the former models establishment and growth while the latter incorporates processes that govern seed dormancy and germination. The guide for TACA model is presented in Chapter 9.

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Chapter 3. Conventional Growth and Yield Modelling

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Forest Inventory Design[2]

Forest inventory design involves the planning of the steps and procedures to be followed to obtain the desired spatial and attributes information of a stand or forest. The forest inventory design process begins with a statement of objectives and ends with a plan for retrieval of the collected and summarized forest inventory information. In addition, the knowledge obtained in conducting a forest inventory is retained to improve future inventories. Forest inventory design has some common steps, regardless of the objectives. However, differences in the objectives of the inventory and the scale of the land to be inventoried (e.g., large scale inventories such as a province or country, or small scale inventories such as a small forest) do affect how each step is to be performed. Following a formal procedure in developing the design of your forest inventory is useful in:

- making sure that the data collected are sufficient to meet the objectives including the perceived uses of the data;
- ensuring that the data are collected in a cost and time effective manner; and
- ensuring that the resulting information can be quickly and easily accessed by resource managers.

Sampling Design

The sampling design steps presented in *Sampling Techniques* by William Cochran (1977) are useful as a basis for structuring the forest inventory design process. The eleven steps are described in order below.

1. ***Define the objectives of the sample.*** A formal statement of the objectives of the forest inventory is required before the survey can be designed. The objectives should be stated as succinctly as possible, so that all of the participants in the survey design and the users of the survey information are clear as to what questions the survey will be used to answer, and what is outside the scope of the survey. In addition, the statement of objectives should include a statement of how quickly the new information is to be retrieved and in what format, so that the data collection and analysis phases of the survey can match the objectives.

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[2] Excerpts from: LeMay, V.M. and P.L. Marshall. 1990. FRST 238: Forest Mensuration Manual.
Published by Distance Education and Technology, Continuing Studies, University of British Columbia.

Without a formal statement of objectives, the reasons for the survey can be forgotten over the duration of the survey. This will be particularly true if there is a long time period from the beginning of the survey to the end of the survey. Also, because the scope of the survey is implied by the statement of objectives, the limitations of the resulting survey information will be defined before the survey is begun.

2. **Define the population to be sampled.** The scope of the survey can also be described by making a formal statement of the population to be sampled. The population must be in accord with the statement of objectives. The statement concerning the population for a forest inventory usually includes a description of the forested land to be inventoried. Also, the various forest resources that will be included in the inventory must be delineated. For example, the inventory objective could be to inventory the timber, vegetation, wildlife, water, and fisheries resources on the forested land. Alternatively, an inventory of only one resource could be conducted, such as an insect inventory, a timber inventory, or a recreational use inventory. For each forest resource that is to be inventoried, specifics about that resource are required in delineating the population. For example, for a recreational use inventory, we could specify that only the car- accessible recreational sites be included. For a timber inventory, we could state that only trees above a certain size would be included in the population.

   In general, the population must be specifically defined, so that the delineation of what items are inside as opposed to outside the population is easily determined.

3. ***Describe the data to be collected*.** Based on the population described and the objectives of the inventory, the variables of interest can be described. Some variables of interest may be estimated from other variables that are easier to measure. For example, if we wish to know timber volume, we would likely measure the DBH and height of trees and estimate volume indirectly. Also, if we wish to know the potential of a site to grow a certain species of tree, we may measure the characteristics of the site, such as soil characteristics, presence of minor vegetation, and climatic variables, in order to estimate the potential productivity of the site. The variables of interest to be measured and the variables to be measured to obtain estimates of other variables of interest must be identified.
4. ***State what degree of precision is desired*.** For each variable that is to be measured in the inventory, the measurement precision must be identified. For example, we may wish to have land area measurements within 0.5 ha. In addition, the sampling precision must be defined; this is used to determine the intensity of the sampling design. In general, if the stated values for measurement and sampling precision are small, more time for data collection and greater funding will be required.
5. ***Describe the methods of measurement.*** The methods of measurement of each variable must be selected. The method must be suitable to meet the precision specified for each variable. Detailed descriptions are usually documented in field manuals.
   The data recording methods (e.g., tally cards, codes) must also be specified. For easier handling of the collected data, the tally card should match the computer files that are to be stored. For many surveys now conducted, the data are stored in the field on hand-held electronic data collectors (EDC's). These EDC's help reduce data recording errors by

providing feedback to the person collecting the data, and by removing manual data entry. Data can be transferred directly from the EDC's to computers.

6. ***Define the sampling frame.*** In defining the sampling frame, the identification of what constitutes a sample observation is made. For example, a tree or a cluster of trees could be one observation. If the forest is being inventoried for wildlife, a flock or a single bird could be one observation. Because forest inventories commonly involve the measurement or estimation of several variables of interest, specification of the sampling frame is difficult. In effect, forest inventories are comprised of several overlapping surveys with each survey having a variable of interest and a sampling frame. For this reason, the sampling frame for forest inventories must be defined for each variable of interest. Often this is included in the description of measurement procedures (field manuals), and must necessarily correspond to the planned analysis of the data collected.
7. ***Select the sample*****.** For each variable of interest, a scheme to select the sample observations must be chosen. To reduce costs, the same sampling design can be used for the collection of several variables. The number of observations to be collected will depend on the specified sampling precision, the sampling frame, and the chosen design.
8. ***Conduct a pilot survey (pre-test) and modify procedures.*** In order to test the survey design, a pilot survey is performed on a subpopulation. The pilot survey will reduce long term costs by ensuring that the survey design meets the objective. If a pilot survey is not performed, there is a chance that the survey will not meet the objectives. An effective pilot survey will include a wide variety of the elements of the population, and all procedures to be followed for the selection, measurement, and analysis of the data. This will allow for modifications to the design if:
    - the objectives are not being met by the design;
    - the population is not easy to identify;
    - the measurement techniques are not applicable for the desired measurement
    - precision;
    - the data recording techniques are difficult or time consuming; or
    - the analysis procedures (computer programs, GIS, statistical procedures) are not suitable for storing, manipulating, or retrieval of the data in order to meet the objectives (in terms of type of data or in terms of time to retrieve the data).

    The pre-test results are then used to modify the survey design accordingly. For example, the objectives could be considered to be too ambitious and would be reduced to more achievable statements; the computer routines to store, analyze, and retrieve the information could be modified; models to estimate variables of interest could be changed, resulting in a change in the variables to be measured in order to estimate these models.

    The pilot survey is essential for evaluating the survey design. If the design is modified greatly, further pretesting using the modified design may be warranted.
9. ***Organize the field work.*** Once the survey design is finalized, the data collection can be undertaken for the entire population.

10. ***Summarize and analyze the data.*** Using the selected procedures, the data can be summarized and analyzed to meet the stated objectives. The results may then be documented for use. Data may also be stored for future use.
11. ***Retain the information about the sampling design (all steps) for future reference***. As a reference for future designs, the design process and the resulting finalized design should be documented. The variability of the variables of interest (e.g., timber volume) from one survey can be used in determining the number of sample observations required to meet the sampling precision set for a survey of a similar forested area. Also, the data that are collected may be suitable for meeting objectives for other forest resources or for the same resources defined for the survey. For example, timber inventory data may be useful for determining the amount of food available for wildlife use.

Attributes of a Good Inventory

1) Is the inventory current?

Currency of data is paramount for most uses (e.g., timber supply analysis, selection of sites for experiments, etc.).

2) Is there a process in place for re-inventory?

A re-inventory process is necessary to insure currency of the inventory.

3) Has the updating process been explicitly addressed?

- If the inventory is not current, has the inventory been updated to the current date?
- Is there a process in place to update the inventory annually for:
    a) human inventions;
    b) natural disturbances; and
    c) stand dynamics (e.g., growth, yield, increment, mortality, changes in species composition).

Since forest land changes occur frequently, even with a re-inventory process in place, the inventory must be updated for disturbance events. The process should be clearly documented, and updates should occur at least annually.

4) Is the inventory complete?

- Does the inventory provide complete spatial coverage?
- Does the inventory provide all of the information anticipated as being necessary for a variety of uses (see section on uses)?
- Is the inventory transparent across administrative boundaries?

An inventory is complete, only insofar as it contains a set of polygon attributes, assessed to a common standard for the province, across all forest lands within the province. For a variety of reasons, inventory of all forest lands may be the responsibility of a number of agencies (*e.g.*, Province, Federal government, industry). Transparency across boundaries facilitates a number of inventory uses.

5) Is the inventory capable of providing information through time?

- Are there processes in place to accurately project future inventory?
- Are there prior records of the inventory (historical) that allow for change analyses?

The current inventory provides the starting point for decisions on how best to make use of forest resources, and what kinds of interventions might be used to create desired future forest conditions. Forecasts of future inventory conditions are important for identifying desired future forest conditions and for determining the associated management interventions that may be required in order to realize these conditions. Historical inventory conditions are used to inform prognostications of how the forest is likely to develop into the future. This information is also used to determine the degree to which past policies produced the then desired future forest conditions. Well-documented observations of change in forest conditions can be used to improve predictions of future forest conditions, and to improve understanding of what might have caused those changes.

6) Is the information provided sufficiently reliable?

- Is it representative / accurate?
- Is it appropriately precise?
- Is documentation of all data collection and analyses procedures readily available?

While it is not often possible to provide a simple accuracy statement for a forest inventory because of the number of variables and the complex network of analyses and models, documentation of the collection and analysis of inventory data helps users to determine the quality of inventory data.

7) Can a variety of users access/query the inventory database?

- Are the inventory data easily obtained (time and cost)?
- Are the inventory data easy to use?
- Are metadata (documentation) provided and easy to understand?

Since forest inventory data are used by a wide variety of users, documentation and ease of use is a critical characteristic of the inventory. Data that are hard to obtain, analyze or understand will result in many complaints and delays in obtaining results.

8) Is the inventory scalable?

- Does the inventory design allow for data collection at the small, medium, and/or large spatial scales?
- Are the data logically consistent across scales?

An inventory design that allows for data collection at a variety of scales allows for flexibility in response to needs and cost (time, money) constraints. Consistency of data across scales both in collection and analysis allows for reporting that is specific locally while remaining applicable at higher levels of abstraction (*i.e.*, local vs. regional representation).

9) Is the inventory sufficient for addressing the forest management issues of today?

The inventory data should be sufficient and easy to use in answering information needs for current management issues.

10) Can the inventory be easily adapted for new variables to address new management issues?

As well as being sufficient for the current issues, the data should be sufficient for providing needed information on emerging management issues.

11) Does the inventory make the best use of appropriate technologies?

The inventory design, including data collection, storage, presentation, and analysis, should utilize the best appropriate technologies to reduce the cost and time to collect and interpret/analyze the forest inventory information.

12) Does the inventory have the ability to provide routine reports on a variety of data at a variety of scales?

Standard reports such as the State of the BC Forests, should be routinely provided as part of the inventory system.

13) Is there a quality assurance system in place?

- Are measurement standards clearly stated?
- Are all inventory models validated (*e.g.*, growth and yield predictions, volume functions)?
- Are data checked for correctness, including coding and transcription errors, consistency of measures across variables, etc.?

A quality assurance system reduces the time spent in analysis of inventory data, and ensures that decisions are made using the best possible inventory with a minimum of errors.

14) Are there provisions for cross-linkages of various types of inventories?

- Are the inventories connected to the best possible base map?
- Is registration of the forest inventory information with other inventories (*e.g.*, topography, ecosystem mapping, soil maps) straightforward (*e.g.*, no need for complex registration using ground control points)?

Registration of a variety of data sources can be very time consuming, and will result in longer lags in providing data for decisions.

Using an Inventory for Growth and Yield Modelling

Tree species composition is an obvious stand characteristic affecting growth and yield in the stand. A pure stand with one species (i.e., plantation), the stand characteristic is easy to quantify, while the mix of species in a stand becomes difficult to characterize the species composition of the stand in any simple way. The most common approach is to classify stands into forest types, also called cover types, based on their species composition. The second factor affecting stand growth and yield is stand age. Generally speaking, trees get bigger and taller as they age, and once they reach their peak growth rate – usually while relatively young – their growth tends to slow as they age. The biggest problem with using stand age as a predictor of growth and yield is that it often is not well-defined. It is fairly straightforward to define and measure the age of a tree, but what is a stand's age? If the stand originated as a plantation, then the majority of the trees may be the same age. However, many stands have a mix of trees of different ages. Even in plantations, many of the trees may be volunteers (of natural origin), and the ages of the trees may be quite variable. Obviously, in uneven-aged stands, stand age is virtually meaningless. Thus, stand age may be very difficult to measure. For these reasons, the average stand diameter at breast height (DBH) or stand volume is sometimes used as a proxy for stand age. An important detail to keep in mind when using age in growth and yield models is the difference between the ages that is typically measured, which is age at DBH, and the total age of the tree.

The third factor affecting stand growth and yield is site quality. The measure of site quality that is used almost universally is the site index, which is the projected height at an index age (typically 25, 50, or 100 years) of dominant and codominant trees of a given species on the site. Site index remains the most widely accepted measure of site quality largely because it works as well or better than most of the alternatives and because it is relatively easy to measure.

The fourth factor affecting forest growth and yield is density, or stocking. Basal area, number of trees per acre (typically only trees over some size), and volume per acre are the most common measures of density. Growth and yield are obviously related to density; growth will be slow in stands that are either too dense or too sparse.

Many other factors affect stand development. Stands of trees are complex biological communities. Obviously, the genetic characteristics of the trees in a stand are important. Also, past management practices can affect current stand development. The obvious example of this is stand origin. Planted stands tend to grow faster than natural stands. Another example is fertilization. Fertilization can be thought of as a change in the site quality. However, the effects of fertilization are generally temporary, while the site quality tends to be quite stable. Forest managers use their understanding of the relationships between these stand characteristics and the stand's growth and development to control the stand in order to achieve whatever end the landowner's objectives dictate. Harvesting is used to control the stand age; thinning is used to control stand density; fertilization to improve site quality; release and prescribed burning to control competition. In order to use these tools effectively, accurate models are needed to predict the specific response that can be expected from different management activities.

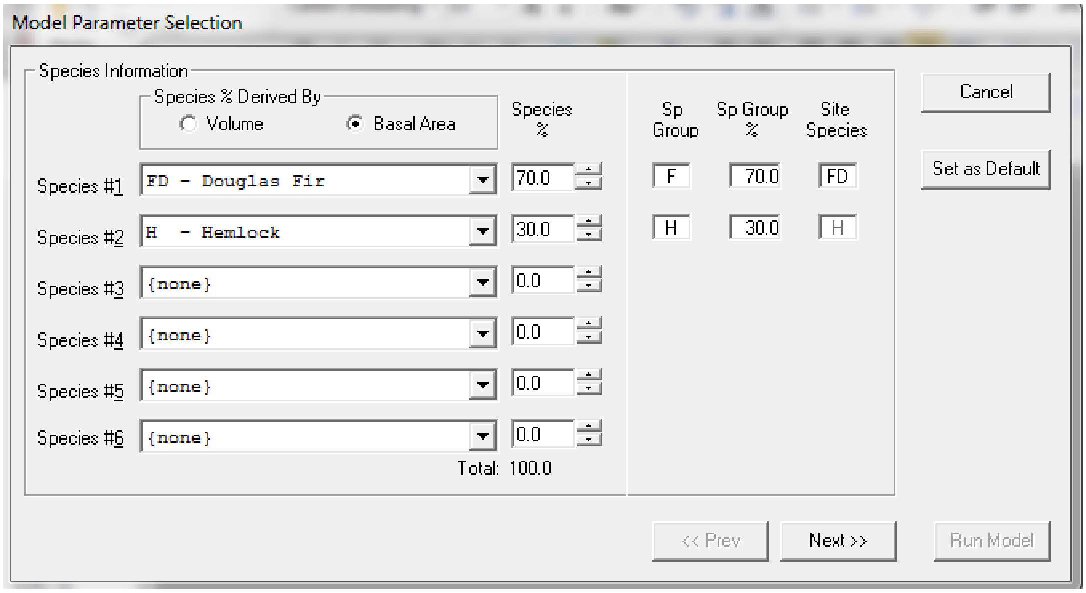
Natural Stand Growth and Yield Models in BC

VDYP7

VDYP7 (Variable Density Yield projection version 7) (Ministry of Forests and Range 2013a) is a growth model that can project an inventory from forest inventory program (FIP), vegetation resource inventory (VRI) unadjusted, or VRI adjusted files. VDYP7 is an empirical growth and yield prediction system for natural stands, based upon temporary inventory sample and permanent growth sample data. The model predicts stand heights, diameters, volumes, and mean annual increments at different utilization levels and ages.

WinVDYP7

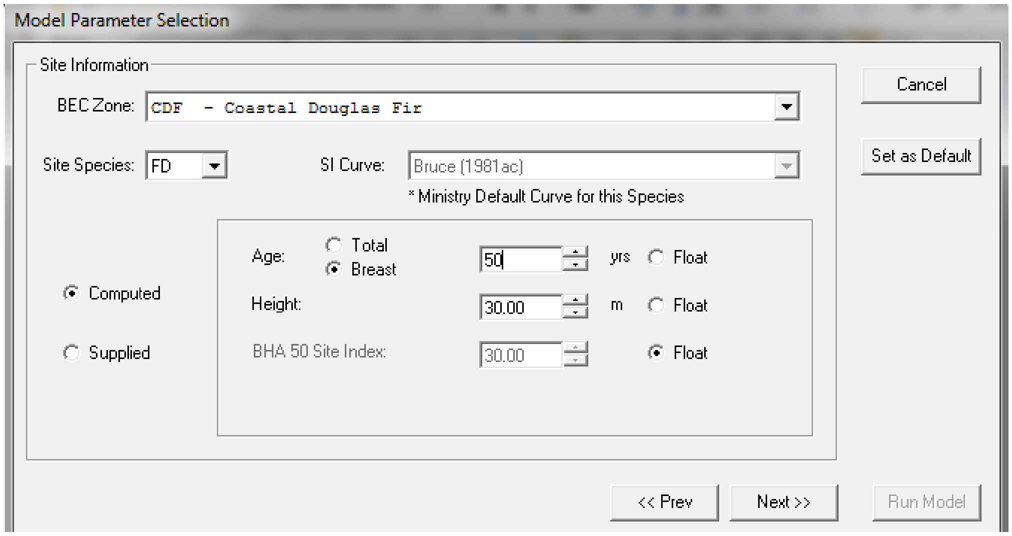
WinVDYP7 (Ministry of Forests and Range 2013b) is an interactive user interface designed to predict yields one stand at a time. The interface prompts the user for typical inventory attributes for the stand including species composition and site index inputs. The user selects attributes to be included in the output table including utilization level. The software then produces a yield table, based on the user input attributes for the age range and increment specified by the user (Figure 3.1-3.4).



Species % Derived By: ○ Volume ● Basal Area

	Species	Species %	Sp Group	Sp Group %	Site Species
Species #1	FD - Douglas Fir	70.0	F	70.0	FD
Species #2	H - Hemlock	30.0	H	30.0	H
Species #3	{none}	0.0			
Species #4	{none}	0.0			
Species #5	{none}	0.0			
Species #6	{none}	0.0			
	Total:	100.0			

Figure 3.1 WinVDYP 7 input data based on basal area calculation for a Douglas-fir (70%) and hemlock (30%) mixed stand



Model Parameter Selection

Site Information

BEC Zone: CDF - Coastal Douglas Fir

Site Species: FD

SI Curve: Bruce (1981ac)

* Ministry Default Curve for this Species

● Computed

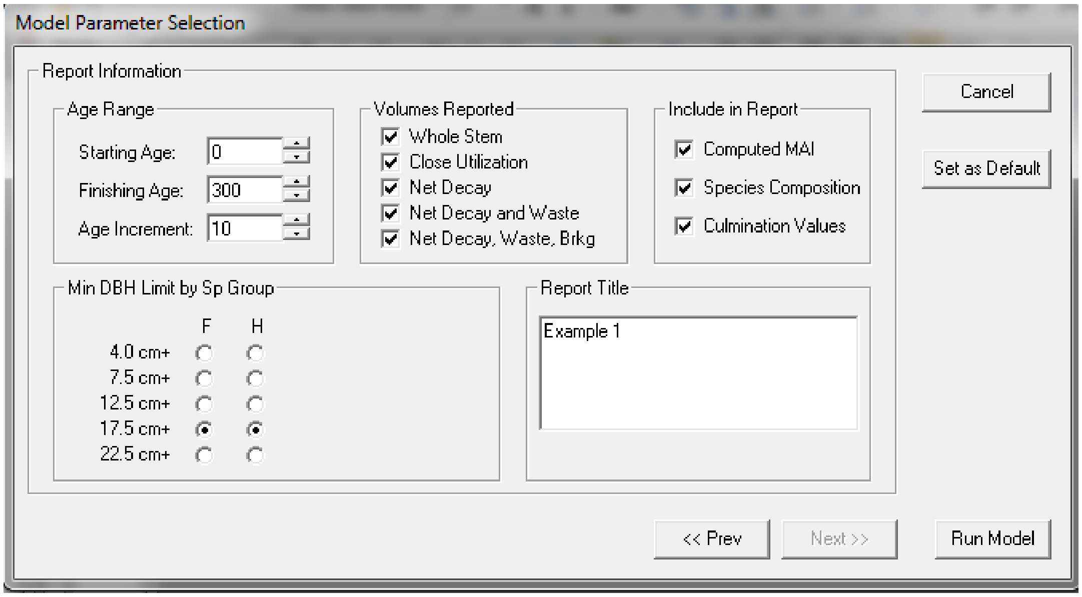
○ Supplied

Age: ○ Total ● Breast 50 yrs ○ Float

Height: 30.00 m ○ Float

BHA 50 Site Index: 30.00 ● Float

Figure 3.2 Site information of the stand including biogeoclimatic zone, site index



Model Parameter Selection

Report Information

Age Range

Starting Age: 0

Finishing Age: 300

Age Increment: 10

Volumes Reported

☑ Whole Stem
☑ Close Utilization
☑ Net Decay
☑ Net Decay and Waste
☑ Net Decay, Waste, Brkg

Include in Report

☑ Computed MAI
☑ Species Composition
☑ Culmination Values

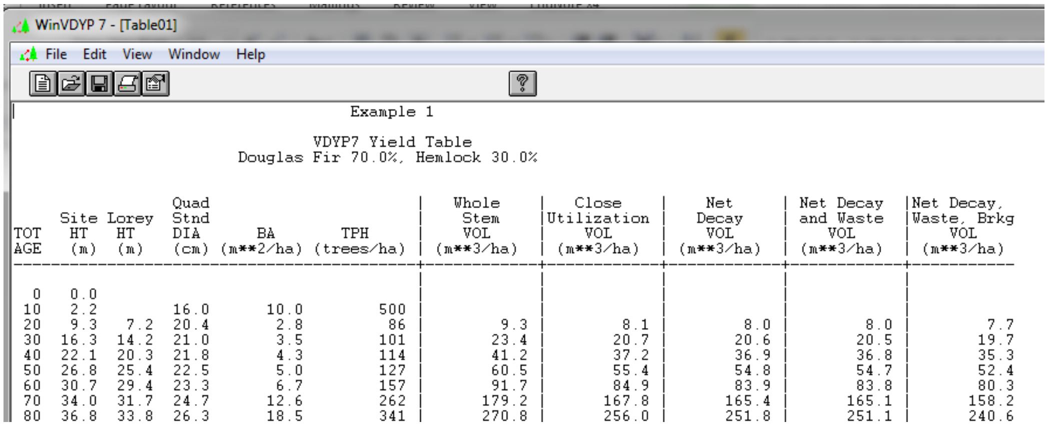
Min DBH Limit by Sp Group

	F	H
4.0 cm+	○	○
7.5 cm+	○	○
12.5 cm+	○	○
17.5 cm+	●	●
22.5 cm+	○	○

Report Title

Example 1

Figure 3.3 Information of model projection and outputs



```
                                    Example 1

                                VDYP7 Yield Table
                        Douglas Fir 70.0%, Hemlock 30.0%

                 Quad                      |   Whole    |   Close    |    Net     | Net Decay  |Net Decay,
     Site Lorey  Stnd                      |    Stem    |Utilization |   Decay    | and Waste  |Waste, Brkg
TOT   HT   HT    DIA      BA       TPH     |    VOL     |    VOL     |    VOL     |    VOL     |    VOL
AGE   (m)  (m)   (cm) (m**2/ha) (trees/ha) | (m**3/ha)  | (m**3/ha)  | (m**3/ha)  | (m**3/ha)  | (m**3/ha)
-------------------------------------------+------------+------------+------------+------------+------------
                                           |            |            |            |            |
  0   0.0                                  |            |            |            |            |
 10   2.2        16.0      10.0        500 |            |            |            |            |
 20   9.3   7.2  20.4       2.8         86 |        9.3 |        8.1 |        8.0 |        8.0 |        7.7
 30  16.3  14.2  21.0       3.5        101 |       23.4 |       20.7 |       20.6 |       20.5 |       19.7
 40  22.1  20.3  21.8       4.3        114 |       41.2 |       37.2 |       36.9 |       36.8 |       35.3
 50  26.8  25.4  22.5       5.0        127 |       60.5 |       55.4 |       54.8 |       54.7 |       52.4
 60  30.7  29.4  23.3       6.7        157 |       91.7 |       84.9 |       83.9 |       83.8 |       80.3
 70  34.0  31.7  24.7      12.6        262 |      179.2 |      167.8 |      165.4 |      165.1 |      158.2
 80  36.8  33.8  26.3      18.5        341 |      270.8 |      256.0 |      251.8 |      251.1 |      240.6
```

Figure 3.4 User defined outputs

Managed Stands Growth and Yield Model in BC

TIPSY, TASS and WinTIPSY

The Table Interpolation Program for Stand Yields (**TIPSY**) (Ministry of Forests, Lands and Natural Resource Operations 2013a) is a growth and yield program that provides electronic access to the managed stand yield tables generated by Tree and stand simulator (TASS) (Ministry of Forests, Lands and Natural Resource Operations 2013b). TIPSY retrieves and interpolates yield tables from its database, customizes the information and displays summaries and graphics for a specific site, species and management regime. Yield tables are available for various even-aged coniferous species of commercial importance growing on the coast and in the interior of British Columbia.

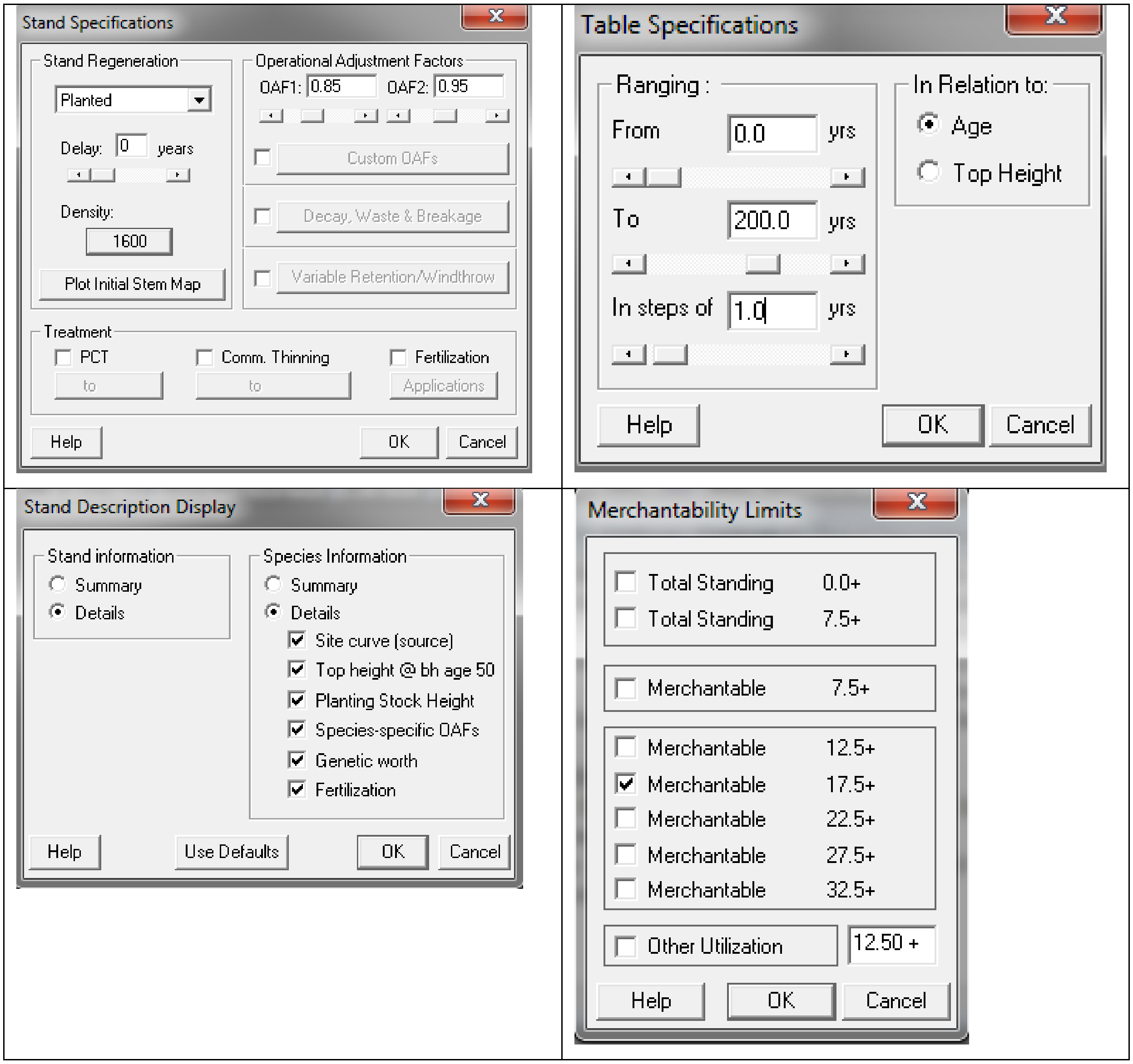
TASS is a computer model that simulates the growth of individual trees and stands in three dimensions. The crowns of individual trees expand and contract asymmetrically as branch extension responds to internal growth processes, physical restrictions imposed by the crowns of competitors, environmental factors and silvicultural practices. The crowns add a shell of foliage each year that benefits the trees in diminishing amounts for several years. The volume increment produced by the foliage is distributed over the bole annually and accumulated to provide tree and stand statistics.

TASS is based on growth trends observed in fully stocked research plots growing in a relatively pest free environment. The yields will be very close to the potential of a specific site, species and management regime. Research Branch maintains the system.

Key features of TIPSY:

- TIPSY retrieves and interpolates yield tables from its database, customizes the information and displays summaries and graphics for a specific site, species and management regime.
- Information can be entered and displayed in either metric or imperial units.

- It uses optional Operational Adjustment Factors (OAFs) to mimic operational conditions. Two types of OAFs are available in TIPSY to account for elements that reduce potential yields. OAF1 is a proportional adjustment that accounts for the reduction of physical growing space due to holes created by rock outcrops, swamps and non-commercial tree competition. OAF2 is an incremental adjustment that accounts for pest damage that increases towards maturity.
- It has a multiple species option oriented to timber supply analysis applications. This option is not recommended for silvicultural applications, since TIPSY does not simulate the growth of multiple species stands biologically. The only biological assumption considered is the site index conversion adjustment among species.



Stand Specifications

Stand Regeneration: Planted
Delay: 0 years
Density: 1600
Operational Adjustment Factors
OAF1: 0.85 OAF2: 0.95
☐ Custom OAFs
☐ Decay, Waste & Breakage
☐ Variable Retention/Windthrow
Treatment
☐ PCT
☐ Comm. Thinning
☐ Fertilization

Table Specifications

Ranging:
From 0.0 yrs
To 200.0 yrs
In steps of 1.0 yrs
In Relation to:
● Age
○ Top Height

Stand Description Display

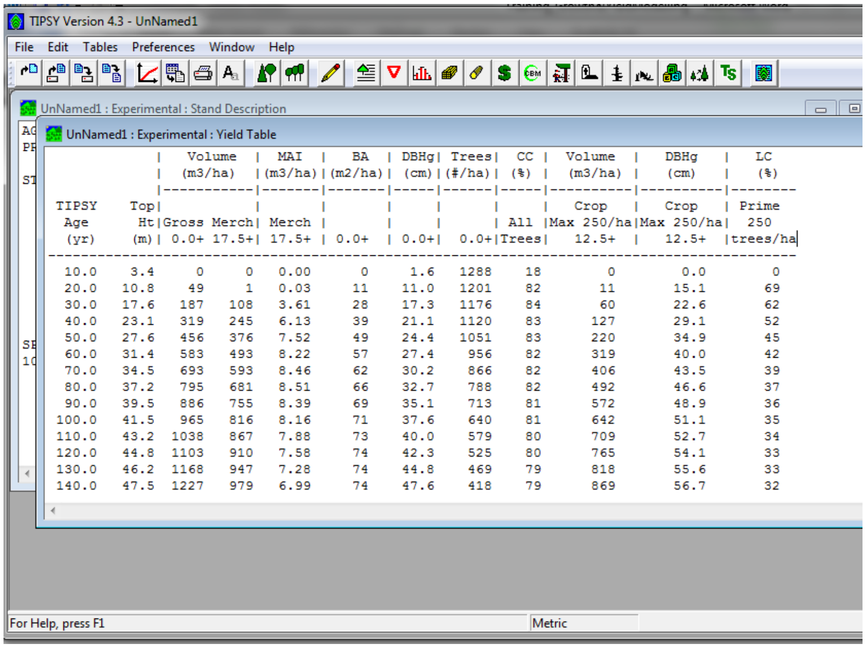
Stand information
○ Summary
● Details
Species Information
○ Summary
● Details
☑ Site curve (source)
☑ Top height @ bh age 50
☑ Planting Stock Height
☑ Species-specific OAFs
☑ Genetic worth
☑ Fertilization

Merchantability Limits

☐ Total Standing 0.0+
☐ Total Standing 7.5+
☐ Merchantable 7.5+
☐ Merchantable 12.5+
☑ Merchantable 17.5+
☐ Merchantable 22.5+
☐ Merchantable 27.5+
☐ Merchantable 32.5+
☐ Other Utilization 12.50 +

Figure 3.5 (a) planting density, adjustment and treatments; (b) Time horizon for the yield projection; (c) stand description and (d) species merchantable limits

WinTIPSY (Mitchell et al. 1995) provides an interactive user interface to calculate growth and yield based on the input (Figure 3.5-3.11).



```
             |   Volume  |  MAI  |   BA  | DBHg| Trees|  CC |  Volume  |   DBHg   |   LC
             |  (m3/ha)  |(m3/ha)|(m2/ha)| (cm)|(#/ha)| (%) |  (m3/ha) |   (cm)   |   (%)
             |-----------|-------|-------|-----|------|-----|----------|----------|--------
 TIPSY    Top|           |       |       |     |      |     |   Crop   |   Crop   | Prime
  Age      Ht|Gross Merch| Merch |       |     |      | All |Max 250/ha|Max 250/ha|  250
  (yr)     (m)| 0.0+ 17.5+| 17.5+ | 0.0+  | 0.0+|  0.0+|Trees|   12.5+  |   12.5+  |trees/ha
-------------------------------------------------------------------------------------------
  10.0    3.4     0     0   0.00      0     1.6   1288    18        0        0.0        0
  20.0   10.8    49     1   0.03     11    11.0   1201    82       11       15.1       69
  30.0   17.6   187   108   3.61     28    17.3   1176    84       60       22.6       62
  40.0   23.1   319   245   6.13     39    21.1   1120    83      127       29.1       52
  50.0   27.6   456   376   7.52     49    24.4   1051    83      220       34.9       45
  60.0   31.4   583   493   8.22     57    27.4    956    82      319       40.0       42
  70.0   34.5   693   593   8.46     62    30.2    866    82      406       43.5       39
  80.0   37.2   795   681   8.51     66    32.7    788    82      492       46.6       37
  90.0   39.5   886   755   8.39     69    35.1    713    81      572       48.9       36
 100.0   41.5   965   816   8.16     71    37.6    640    81      642       51.1       35
 110.0   43.2  1038   867   7.88     73    40.0    579    80      709       52.7       34
 120.0   44.8  1103   910   7.58     74    42.3    525    80      765       54.1       33
 130.0   46.2  1168   947   7.28     74    44.8    469    79      818       55.6       33
 140.0   47.5  1227   979   6.99     74    47.6    418    79      869       56.7       32
```

Figure 3.6 Output yield table

References

Cochran, W.G. 1977. Sampling techniques. Wiley , New York, NY.

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Mitchell, K.J., and S.E. Grout. 1995. User's guide for producing managed stand yield tables for WinTIPSY 1.3 under Microsoft Windows. B.C. Min. For., Victoria, B.C .

Chapter 4. ClimateAP for Downscaling Historical and Future Climate Data

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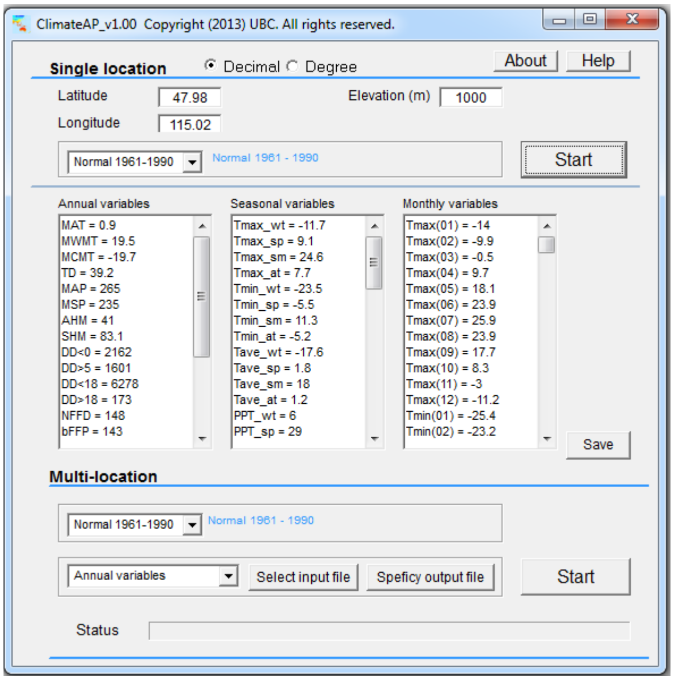
An Overview of ClimateAP

ClimateAP is a standalone MS Windows® application written in Visual Basic 6.0. The interface of the program is shown in Figure 4.1. ClimateAP extracts and downscales PRISM (Daly et al. 2002) and WorldClim (Hijmans et al. 2005) 1961-1990 monthly normal data (2.5 x 2.5 arcmin) to scale-free and calculates seasonal and annual climate variables for specific locations based on latitude, longitude and elevation (optional). ClimateAP covers the Asia Pacific region (Figure 4.2).

The program uses the scale-free data as baseline in combination with monthly anomaly data (Mitchell and Jones 2005) of individual years to calculate historical monthly, seasonal and annual climate variables for individual years and periods between 1901-2009. This program also downscales and integrates future climate datasets for 2020s (2010-2039), 2050s (2040-69) and 2080s (2070-2099) generated by various global circulation models. The output of the program includes both directly calculated and derived climate variables.



● Decimal ○ Degree

Latitude 47.98

Longitude 115.02

Elevation (m) 1000

Normal 1961-1990 ▾ Normal 1961 - 1990

Annual variables

```
MAT = 0.9
MWMT = 19.5
MCMT = -19.7
TD = 39.2
MAP = 265
MSP = 235
AHM = 41
SHM = 83.1
DD<0 = 2162
DD>5 = 1601
DD<18 = 6278
DD>18 = 173
NFFD = 148
bFFP = 143
```

Seasonal variables

```
Tmax_wt = -11.7
Tmax_sp = 9.1
Tmax_sm = 24.6
Tmax_at = 7.7
Tmin_wt = -23.5
Tmin_sp = -5.5
Tmin_sm = 11.3
Tmin_at = -5.2
Tave_wt = -17.6
Tave_sp = 1.8
Tave_sm = 18
Tave_at = 1.2
PPT_wt = 6
PPT_sp = 29
```

Monthly variables

```
Tmax(01) = -14
Tmax(02) = -9.9
Tmax(03) = -0.5
Tmax(04) = 9.7
Tmax(05) = 18.1
Tmax(06) = 23.9
Tmax(07) = 25.9
Tmax(08) = 23.9
Tmax(09) = 17.7
Tmax(10) = 8.3
Tmax(11) = -3
Tmax(12) = -11.2
Tmin(01) = -25.4
Tmin(02) = -23.2
```

Normal 1961-1990 ▾ Normal 1961 - 1990

Annual variables ▾

Figure 4.1 The interface of ClimateAP version 1.00

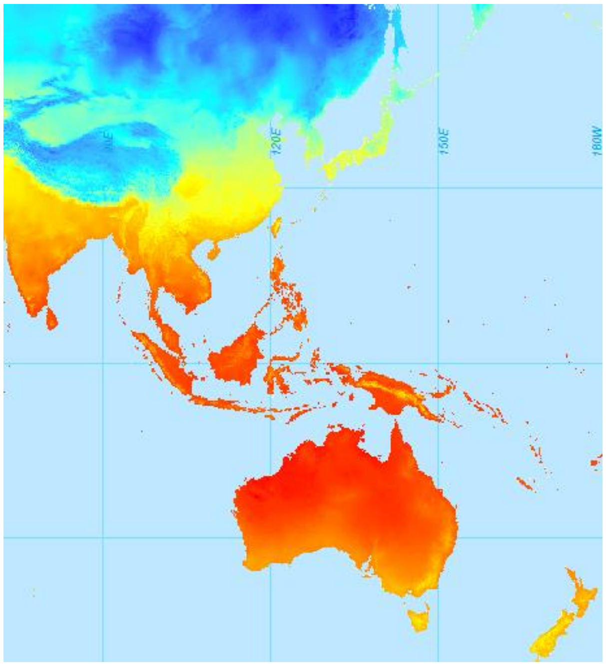


Figure 4.2 The coverage of ClimateAP.

Climate Data Extrapolation

Baseline data

ClimateAP uses the best available 30-year-normal monthly climate data for the reference period 1961-1990 as the baseline data. The PRISM monthly data are only available for China and Mongolia. The monthly climate data from WorldClim were used for the rest part of the region. The baseline climate data are at the resolution of 0.25 x 0.25 arcminutes (about 4 km). The climate variables obtained from these data sources included three primary climate variables: monthly minimum temperatures (Tmin01-12) and monthly maximum temperatures (Tmax01-12) and monthly precipitation (Pre01-12).

Downscaling

ClimateAP uses a combination of bilinear interpolation and dynamic local regression approaches to downscale the baseline monthly grid data to scale-free point data. Instead of applying the midpoint values of each 4 × 4-km tile to all points within each tile, we used bilinear interpolation method to interpolate values between midpoints of the 4 × 4-km grids as illustrated in Figure 4.3.

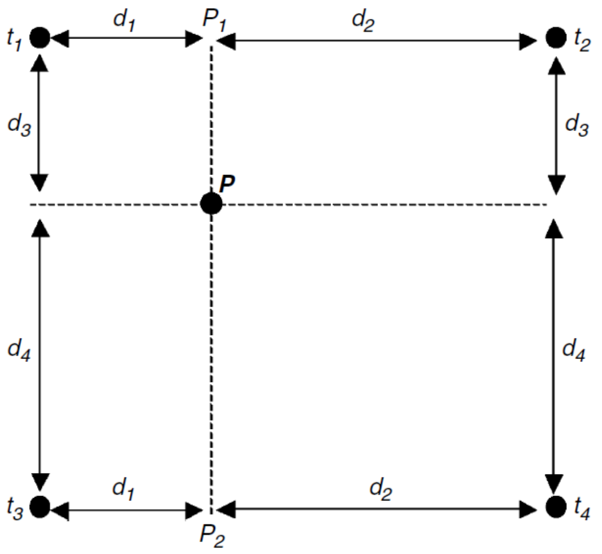


Figure 4.3 Illustration of bilinear interpolation of the baseline climate data (Wang et al. 2006)

P is the location for prediction; t1, t2, t3, and t4 are the values of climate variables at the centers of the four neighboring tiles; d1, d2, d3, and d4 are the relative spatial distances. P1 and P2 are predictions based on simple linear interpolations of the climate variable values t1 and t2, and t3 and t4, respectively, and the prediction for *P* is the simple linear interpolation between *P1* and *P2*.

After the grid data, including elevation, are interpolated into continuous surfaces, we applied dynamic local regression to estimate lapse rates for the location of interest to account for elevational effects. ClimateAP retrieves monthly climate data and elevation values from 9 closest neighbors and calculates differences in climate variables and elevation between all possible pairs. A simple linear regression of the differences in a climate variable on the difference in elevation allows the estimation of the lapse rate for the climate variable. A lapse rate is estimated for each of the 36 monthly primary climate variables. Figure 4.4 shows the relationships between the differences in temperature and precipitation and the differences in elevation.

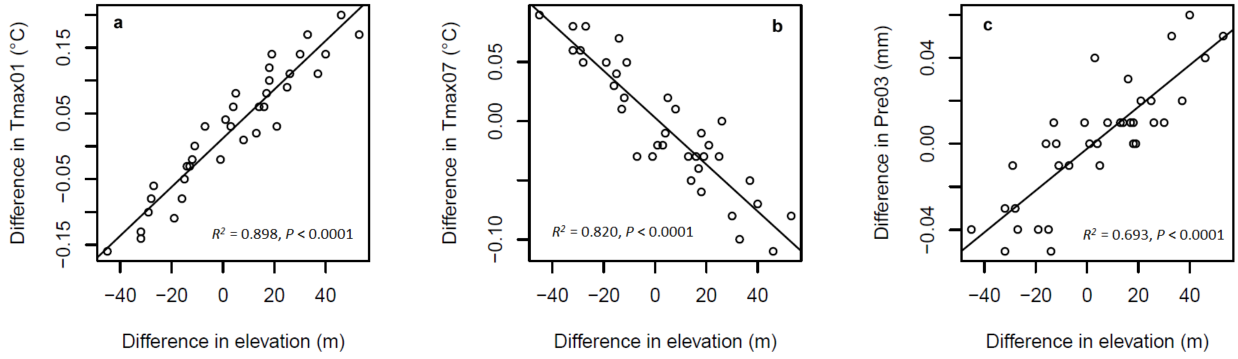


Figure 4.4 Relationships between the differences in maximum temperature in January (a) and July (b), and precipitation in March (c), and the differences in elevation.

The effect of the downscaling can be visualized in Figure 4.5. The limitation of the relatively low resolution of the grid data and power of the downscaling approach applied in ClimateAP can be clearly seen on the map.

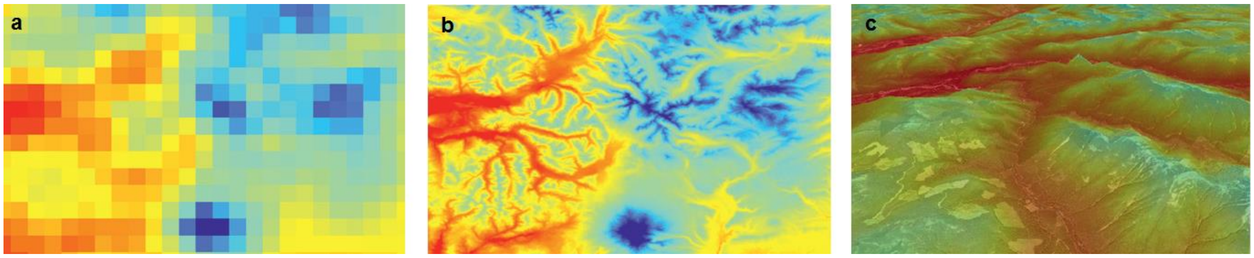


Figure 4.5 Illustration of the effect of downscaling approach applied in ClimateAP shown on the maps: a) mean annual temperature (MAT) of the baseline data at 4 x 4 km; b) downscaled MAT through ClimateAP (100 x 100 m); c) downscaled MAT (100 x 100 m) by ClimateAP

Calculated climate variables

The baseline data contain 36 primary monthly climate variables including monthly maximum (Tmax01-12) and minimum (Tmin01-12) temperatures and precipitation (PPT01-12). ClimateAP calculates many additional climate variables at run-time based on these primary climate variables listed in Table 4.1.

Table 4.1 Climate variables directly calculated based on the 36 primary climate variables included in the baseline data.

Variable category	Variable short name	Variable long name
Annual	MAT	Mean annual temperature
	MWMT	Mean warmest month temperature
	MCMT	Mean coldest month temperature
	TD	Continentality, temperature difference between MWMT and MCMT
	MAP	Mean annual precipitation
	AHM	Annual heat-moisture index (MAT+10)/(MAP/1000))
Seasonal	Tmax_DJF – SON	Tmax for December to February, and so on
	Tmin_DJF – SON	Tmin for December to February, and so on
	Tave_DJF – SON	Tave for December to February, and so on
	PPT_ DJF – SON	PPT for December to February, and so on
Monthly	Tave01-12	Monthly average temperatures

Derived climate variables

In addition to the primary climate variables included in the baseline data, directly calculated variables using the primary variables, ClimateAP also derived many biologically relevant climate variables from monthly climate variables, such degree-days, and number of frost-free days, extreme temperatures and moisture deficit. These variables can be calculated from daily climate data. However, daily data are not available in ClimateAP or other interpolated climate data. We developed functions based on the relationships between these climate variables calculated from weather station data and the monthly climate variables from the same weather stations.

In order to model these relationships, we obtained daily climate data from 1,805 weather stations in Asia Pacific region. The distribution of the weather stations is shown in Figure 4.6.

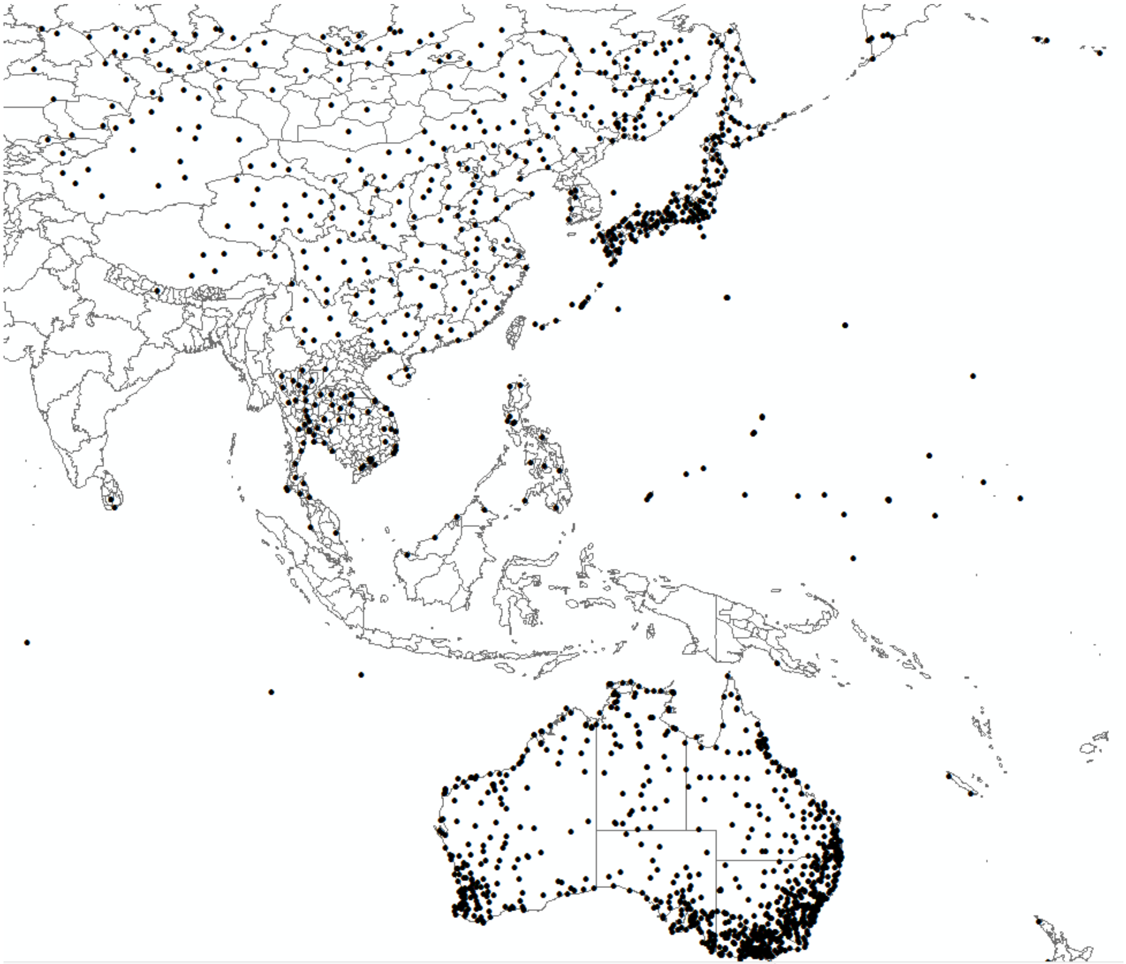


Figure 4.6 The distribution of weather stations that were used to derive the relationships between biologically relevant climate variables and monthly climate variables

Due to the wide range of variation in climate variables in the Asia Pacific region, no single linear, polynomial or nonlinear function can reflect such relationships for most of these climate variables. Thus, we applied piecewise functions, which are combinations of a linear function and a sigma nonlinear function, to model these relationships. Some of these relationships are demonstrated in Figure 4.7.

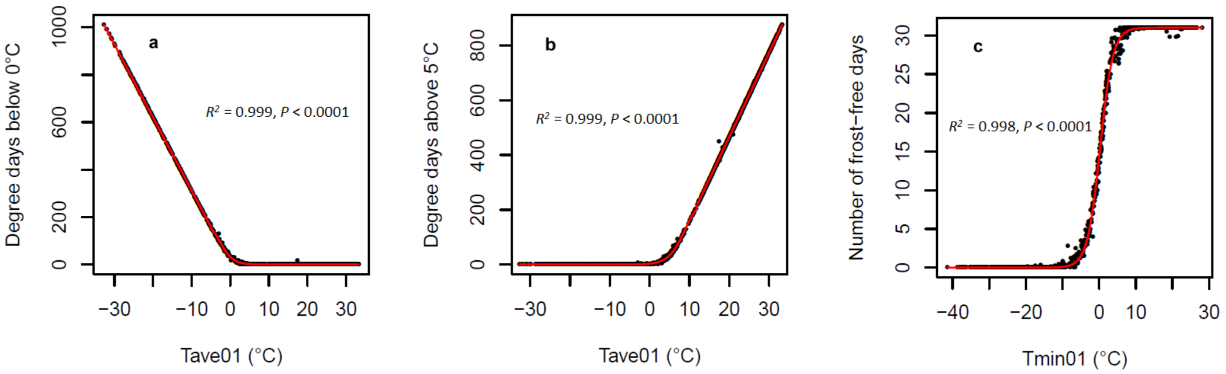


Figure 4.7 Relationships between derived monthly climate variables and monthly climate variables for degree-day below 0°C, degree-day above 5°C and number of frost-free days in January

Table 4.2 Annual climate variables derived based on relationships between calculated climate variables from daily data and primary monthly climate variables based on observation from weather stations.

Variable category	Variable short name	Variable long name
Annual	DD<0 (DD_0)	Degree-days below 0°C, chilling degree-days
	DD>5 (DD5)	degree-days above 5°C, growing degree-days
	DD<18 (DD_18)	degree-days below 18°C, heating degree-days
	DD>18 (DD18)	degree-days above 18°C, cooling degree-days
	NFFD	the number of frost-free days
	PAS	Precipitation as snow (mm)
	EMT	Extreme minimum temperature over 30 years.
	EXT	Extreme minimum temperature over 30 years.
	Eref	Hargreaves reference evaporation
	CMD	Hargreaves climatic moisture deficit

Derived climate variables generated by ClimateAP includes climate variable at annual, seasonal and monthly time scales (Table 4.2). Two of these variables are not based on the relationships modeled from weather station data. They are Hargreaves reference evaporation and Hargreaves climatic moisture deficit (Wang et al. 2012).

Climate variables for historical years and future periods

Monthly temperature and precipitation data for 1901-2009 used in ClimateAP are based on Mitchell and Jones's (2005) interpolated historical data at 0.5 x 0.5° resolution (CRU TS 3.1). We are in process to develop similar datasets for 2010-2012. Temperature was expressed as a difference in degrees Celsius, and the delta surfaces for precipitation were calculated as percentage difference from the 1961-1990 normal values, e.g. -50% represents half and 200% twice the normal precipitation value for a particular month.

The climate data for future periods were from General Circulation Models (GCMs) from the IPCC Fourth Assessment (IPCC 2007). Three emission scenarios (A1B, A2 and B1) were included for a Canadian third generation of Coupled Global Climate Model (CGCM3). Our objective is to include multiple GCMs from the IPCC Fifth Assessment.

ClimateAP integrates both historical and future climate data with a delta method. Anomaly grids are interpolated using bilinear interpolation in run-time to avoid step-artifacts at grid boundaries, and the difference is added to the downscaled baseline climate normal data (scale-free) to arrive at the final climate surface with high-resolution (Figure 4.8).

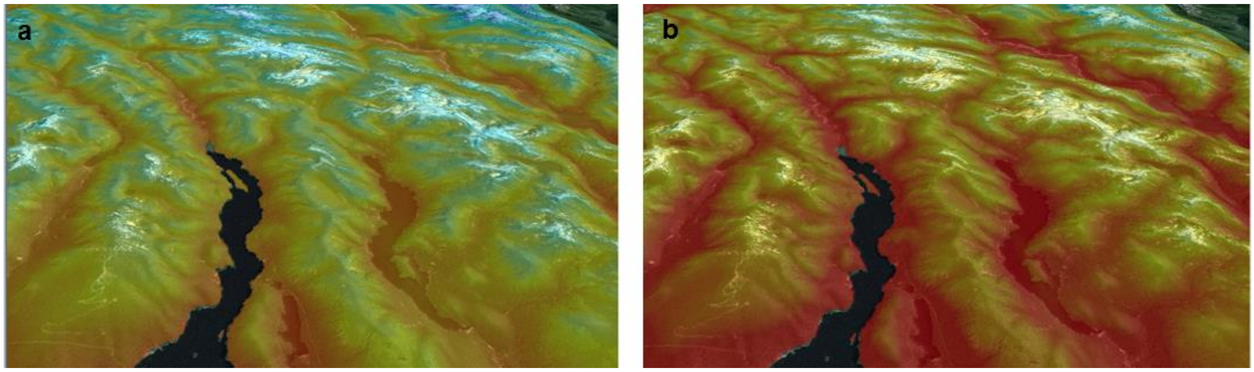


Figure 4.8 Demonstration of the high-resolution climate data (MAT) generated by ClimateAP for the reference (1961-1990) and a future period (2050s).

With this approach, the original baseline data (absolute values for 1961-1990 normal period) of the historical data and future projections are replaced by scale-free climate data generated by ClimateAP and improve the prediction accuracy.

Improvements of ClimateAP output for historical and future climate data over the original CRU and GCM data for the baseline data is shown in Figure 4.9. On average over the 1805 weather stations tested, the prediction standard errors were reduced by 0.5°C for monthly minimum temperatures, 0.8°C for monthly maximum temperatures, 21mm for monthly precipitation. The amount of improvement was even greater as expected; it was up to 2°C for monthly temperatures and 35mm for monthly precipitation on overage. For example, we found in our previous study that the error in mean annual temperature associated with the baseline climate data is 6°C at the Vancouver International Airport (Figure 4.10).

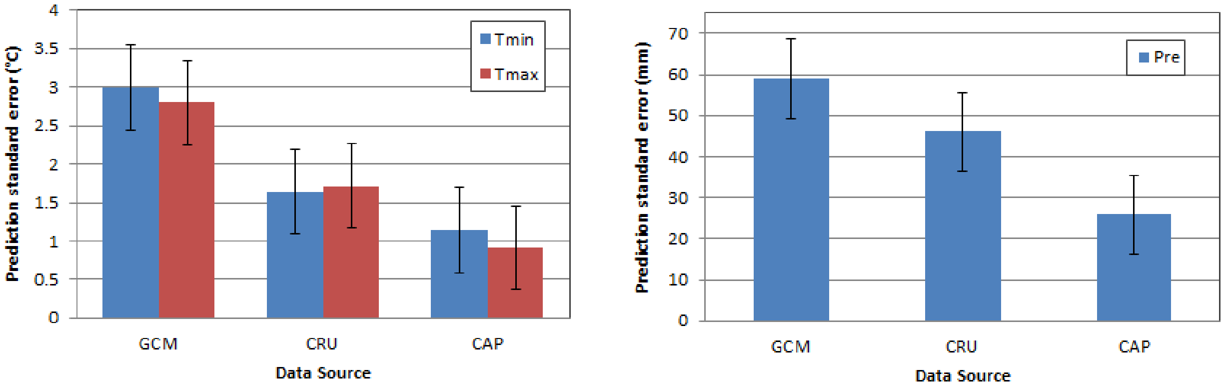


Figure 4.9 Comparisons in prediction standard errors among three data sources: IPCC GCM predictions (GCM), Climate Research Unit (CRU) and ClimateAP output (CAP).

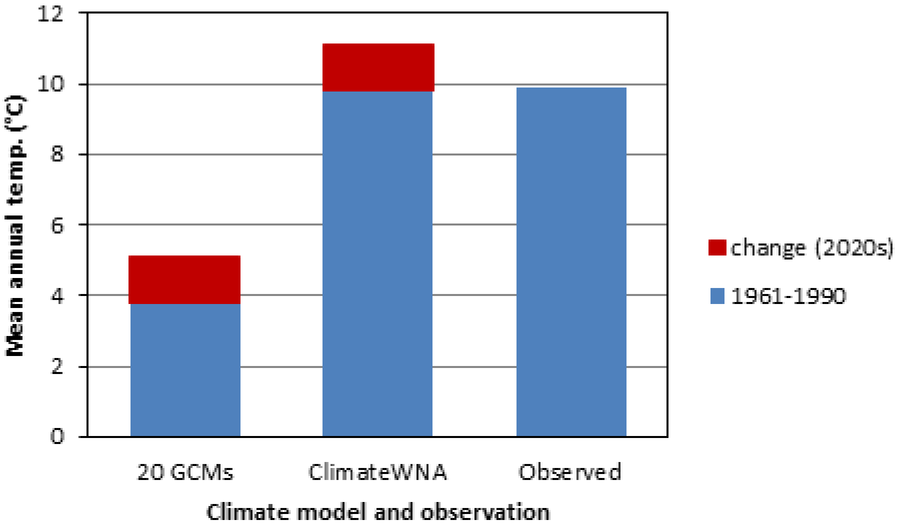


Figure 4.10 Illustration of ClimateAP downscaling method for GCM projections by removing errors in mean annual temperature associated with baseline climate data. Data shown are from a previous study using ClimateWNA that applied the same delta approach as ClimateAP.

Guide for ClimateAP

Installation

The installation of ClimateAP is very simple because it does not require installation process. That is why we stick with Visual Basic 6 instead of the new version of VB.NET. Users need simply copy two files (“ClimateAP_v1.00.exe” and “Help.rtf”) and three subfolders (“prismdat”, “perioddat”, GCMdat”) into the same location on your hard disk and double click the file ClimateAP_v1.00.exe”. The program can run from USB drive, but it does not work properly on network drives.

In case it does not run on your computer, you may need to download the library file and install it. http://www.genetics.forestry.ubc.ca/cfcg/res_climate-models/libraryfiles.exe.

Interactive mode

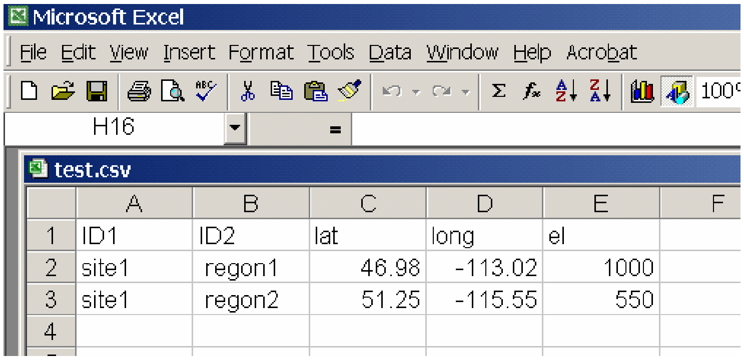
It is easier to use the interactive mode for a single location or a small number of locations. The users just need to input the latitude, longitude and elevation (optional), and click the “Start” button. Options are available for latitude and longitude input in either decimal degree or degree-minute-second. If elevation is missing, the elevation in the baseline data will be used and no elevational adjustment will be performed. A drop-down box is for choosing the targeted period.

By clicking the “Start” button, climate variables for all the three time scales (annual, seasonal and monthly) will be displayed on the screen. The output can be copy and passed to a file. It can also be saved to a Comma-separated-value (csv) file by clicking the “Save button”.

Multi-location mode

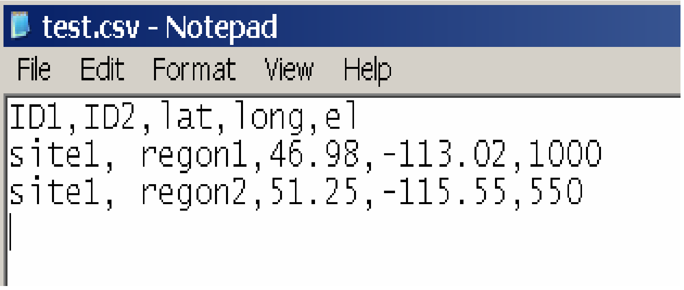
It is much more efficient to the Multi-location mode to process multiple locations than to use the Interactive mode. The program does not have an upper limit for the number of locations to be processed. In order to use the Multi-location mode, a coordinate input file needs to be prepared.

The input file requires two columns of IDs, latitude and longitude in decimal degree, and elevation in meter. A header row is also required. It can be prepared in MS Excel,



	A	B	C	D	E	F
1	ID1	ID2	lat	long	el	
2	site1	regon1	46.98	-113.02	1000	
3	site1	regon2	51.25	-115.55	550	
4						

or in any text editor:



```
ID1,ID2,lat,long,el
site1, regon1,46.98,-113.02,1000
site1, regon2,51.25,-115.55,550
```

If the input file is prepared in Excel, it needs to be saved in CSV format. If it is prepared in a text editor, the columns have to be separated by commas.

When the input file is ready, users can select a target year or a period, then click on Select input file to read your spreadsheet and on Specify output file to specify your output file folder and file. By clicking the Calculate button, output climate variables will be generated.

Applications

Climate is the primary factor regulating the geographic distributions of forest ecosystems and tree species (Woodward 1987, McKenney et al. 2007). It is also the main driver affecting the health and productivity of trees and other plants. Due to the difficulty in accessing climate data, research scientists have been using geographic variables, such as latitude, longitudes and elevation, as substitutes to climate variables for experimental design and data analysis. However, results obtained from such studies are limited to specific locations. For example, a relationship developed between the performance of a plant and elevation gradient in Kunming, China will not be valid in Beijing. This is because the effect of elevation on climate is very different between the south and north. In contrast, a relationship between the performance of a plant and climate variables will be applicable to anywhere. In addition, a relationship with geographic variables will not be useful for predicting the impact of climate change.

ClimateAP makes our access to climate variables as easy as to geographic variables. Therefore, it can be used for different areas of research and applications, such as:

1. Climate based experimental design and data analysis. Climatically based experiments will be more effective than geographically based in most cases. This is because the effect of climate on tree health and productivity is more direct than that of geographic variables. A typical example is the experimental design of the Lodgepole pine provenance trial in British Columbia. It has 60 test sites in the province and well represents the geographic distribution of this species. However, when plot the test sites against the mean annual temperature (MAT), the most important climate variable for this species, we found that the majority of the tests are located in a very narrow range of MAT and are redundant (Figure 4.11). A climatically based experimental design would save 60-70% of the cost.

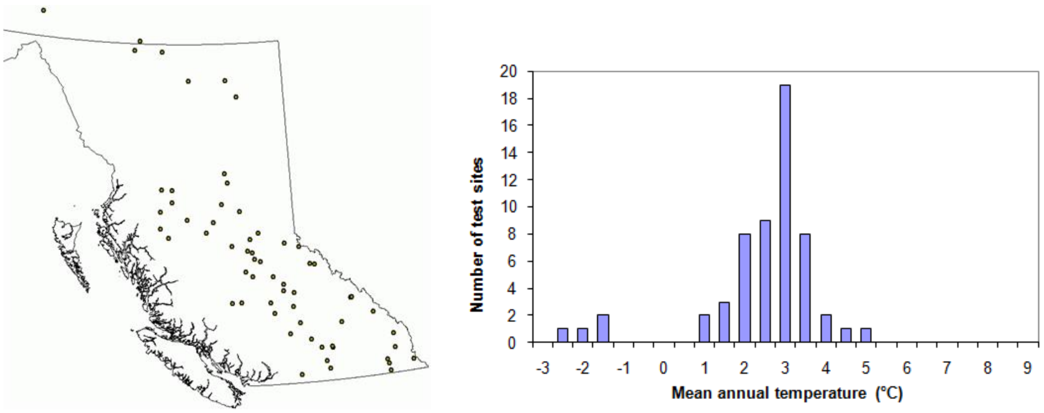


Figure 4.11 Geographic (left) and climatic (right) distributions of planting sites of the provenance test in British Columbia.

2. Generating climate surfaces. The output of ClimateAP is in the format of spreadsheet file. It can easily be imported to ArcGIS to generate maps. The resolution of the map depends on the resolution of the input file, which means that it is up to the user to determine the resolution of the climate surface.
3. Modelling climate niches for ecosystems and species. Such modelling exercises require climate data to well match the actual locations of the vegetation data. The scale-free climate data generated by ClimateAP can well meet this requirement. More details can be found in the next section.

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Chapter 5. Carbon Budget Modelling[3]

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Introduction to CBM-CFS3

The Carbon Budget Model-Canadian Forest Sector 3 (CBM-CFS3) is a yield data driven model with explicit simulation of dead organic matter (DOM) dynamics. It simulates the C dynamics of above- and belowground biomass and DOM, including soils, and can represent both stand- and landscape-level forest dynamics. As a forest C accounting framework, it tracks C stocks, transfers between pools, and emissions of carbon dioxide (CO_2), methane (CH_4), and carbon monoxide (CO) (Figure 5.1).

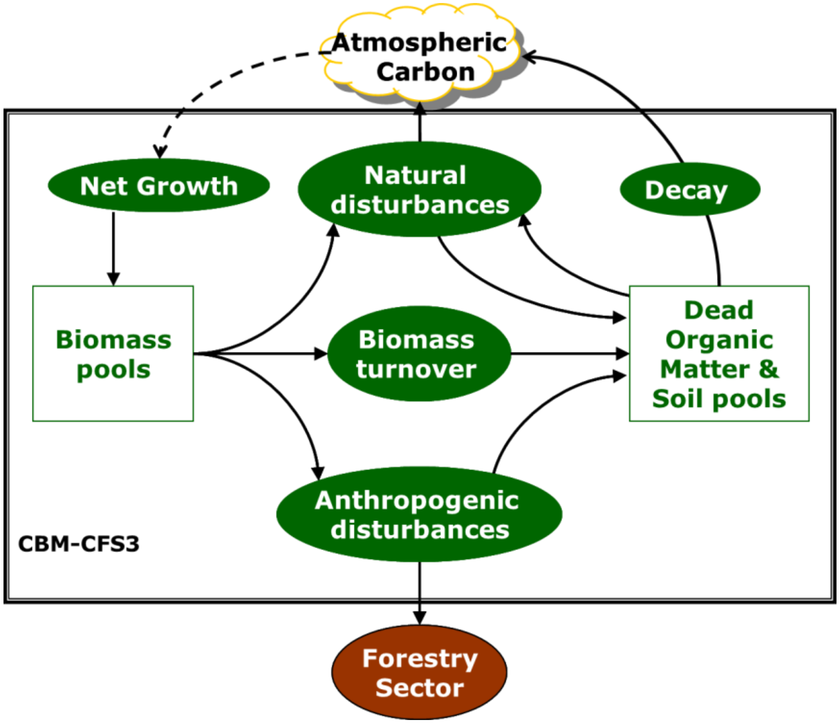

Figure 5.1 CBM-CFS3 carbon pools (boxes), processes (oval).

Simulation of growth causes carbon to enter the forest ecosystem as living biomass. Simulation of turnover and disturbance processes causes the transfers of carbon from biomass to DOM

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[3] Excerpts from: Kurz, W.A., C.C. Dymond, T.M. White, G. Stinson, C.H. Shaw, G.J. Rampley, C. Smyth, B.N. Simpson, E.T. Neilson, J.A. Trofymow, J. Metsaranta, and M.J. Apps. 2009. CBM-CFS3: A model of carbon-dynamics in forestry and land-use change implementing IPCC standards. Ecological Modelling, 220(4): 480-504.

pools. Natural disturbances can cause the loss of carbon from the ecosystem as gaseous emissions (i.e., the smoke from a forest fire). Harvesting causes the loss of carbon from the ecosystem to the forestry sector (i.e., wood processing the secondary users). Carbon is also lost from the ecosystem due to decay of the DOM and soil organic carbon.

Representation of Land Areas

Forest landscapes are typically comprised of large numbers of forest stands—communities of trees that are homogeneous enough to be treated as a unit. In the CBM-CFS3 modelling framework, a forest landscape comprised of administrative regions and ecological regions that are represented as a collection of spatial units (Figure 5.2). Each stand in the study area is spatially referenced to the spatial unit in which it is located. Disturbance events can target stands within a spatial unit or group of spatial units (disturbance group). All input data and parameters are referenced to individual spatial units, or to group of spatial units (Figure 5.2).

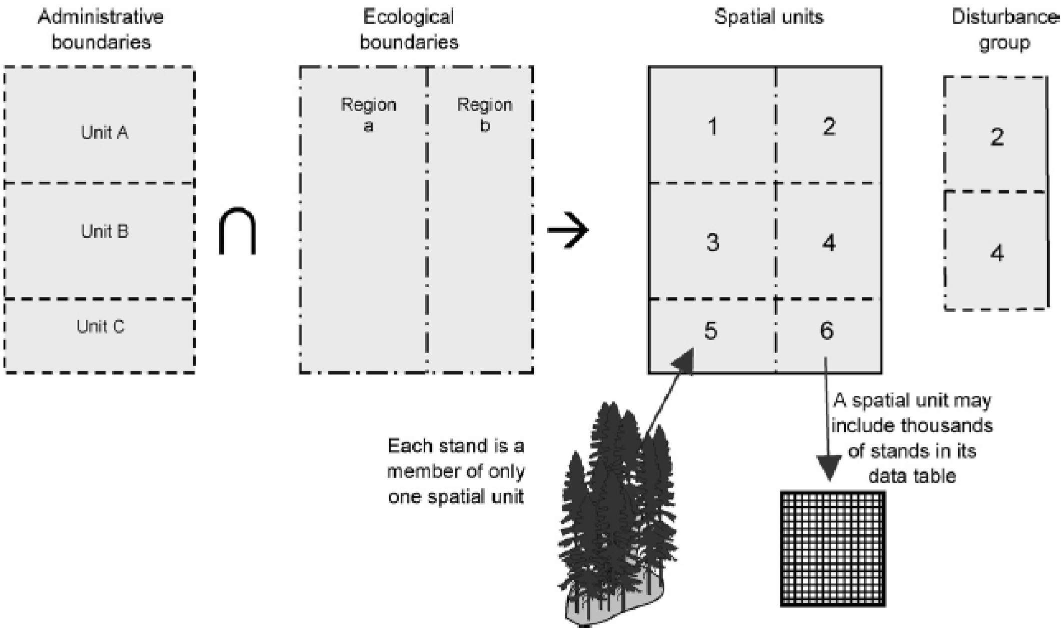

Figure 5.2 A representation of forests stands in CBM.Biomass and decay dynamics.

The CBM-CFS3 simulates annual changes in each stand’s C stocks of each pool that occur due to growth, biomass turnover, litterfall, transfer and decomposition (Figure 5.3). Simulation of growth causes carbon to enter the forest ecosystem and it is distributed among 10 different biomass pools. Simulation of turnover and disturbance processes causes the transfers of carbon from biomass to DOM pools. Disturbances can also cause the loss of carbon from the ecosystem as gaseous and disturbance. Carbon that remains in the ecosystem eventually ends up in the belowground slow DOM pool.

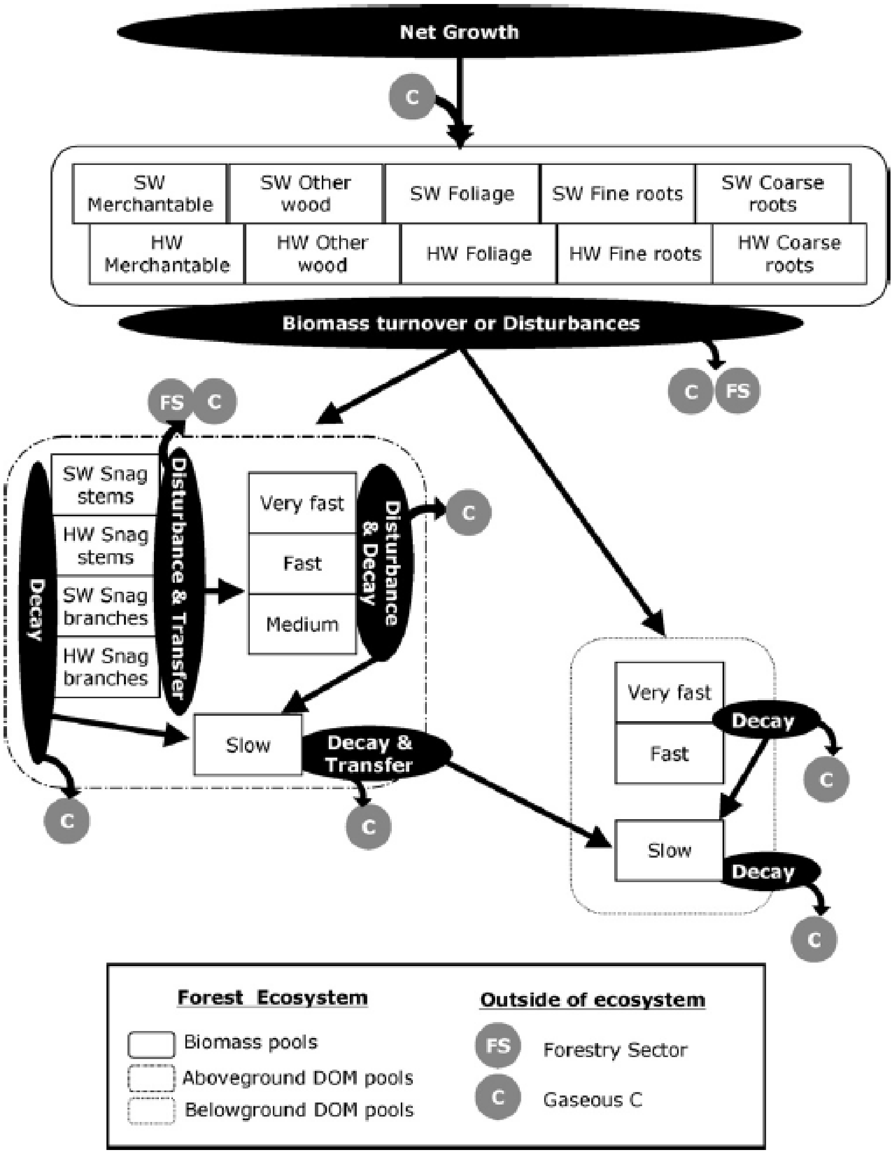

Figure 5.3 Conceptual design of CBM carbon pools and transfers among pools. The Rectangles represent pools, round-rectangles represent groups of pools, arrows represent the movement of C between groups of pools, ovals represent the simulated processes and circles represent losses from the ecosystem.

Pools

The CBM-CFS3 tracks 10 biomass and 11DOMC pools (Table 5.1). The living biomass pools are tracked separately for hardwood and softwoods within each stand using the following categories: merchantable stemwood, other wood, foliage, coarse roots and fine roots. The

DOM pools are categorized by the type of material they contain and by their anticipated rate of decay.

Table 5.1 CBM carbon pools and IPCC defined carbon pools.

CBM carbon pools	Description	IPCC Pool
Merchantable + bark (SW + HW) Other wood + bark (SW + HW)	Live merchantable stemwood plus bark; live branches, stumps, and small trees + bark	Aboveground biomass
Foliage (SW or HW)	Live foliage	Aboveground biomass
Fine roots (SW or HW)	Live roots (<5 mm diameter)	Belowground biomass
Coarse roots (SW or HW)	Live roots (≥ 5 mm diameter)	Belowground biomass
Snag stems DOM (SW or HW)	Dead standing merchantable stemwood + bark	Dead wood
Snag branches DOM (SW or HW)	Dead branches, stumps and small trees + bark	Dead wood
Medium DOM	Coarse woody debris on the ground	Dead wood
Aboveground fast DOM	Fine and small debris + dead coarse roots in the forest floor, ~[5, 75) mm	Litter
Aboveground very fast DOM	The L horizon foliar litter + dead fine roots	Litter
Belowground fast DOM	F, H and O horizons	Litter
Belowground fast DOM	Dead coarse roots in the soil	Dead wood
Belowground very fast DOM	Dead fine roots in the soil	Soil organic matter
Belowground slow DOM	Humified organic matter in the mineral soil	Soil organic matter

Growth

Forest management agencies and industry have built up large libraries of yield tables to describe the accumulation of volume in the merchantable portion of tree stems as a function of stand age. The merchantable volume yield tables are associated with forest stands inside the CBM-CFS3 using classifier values (such as genus and site-class), similar to the approach in many timber supply analysis models. The model assumes that the values reported in the yield tables represent gross merchantable wood volume (including decay, waste and breakage), except in British Columbia where it assumes yield table values represent net merchantable wood volume (Power and Gillis, 2006). Note that stand volumes reported in the inventory are not used to estimate growth, only the age from the inventory and the volume from the yield table is used.

While typical yield tables are in units of merchantable volume, estimates of C in all components of the stand are required to represent the C dynamics. The CBM-CFS3 uses equations developed by Boudewyn et al. (2007) to estimate aboveground biomass from the yield tables provided as model input. We used this approach because these volume-to-biomass equations are comprehensive—models were developed for all forest stand types found in Canada and require as input only information commonly available in typical Canadian forest inventory datasets. The development of the models relied on the availability of a large number of permanent and temporary sample plots (over 133,000) containing individual tree measurements (Boudewyn et al., 2007). Plots came from all provinces and territories in Canada except the Northwest Territories and Nunavut, with most from Quebec, about 15% from B.C. and the rest from the remaining jurisdictions. The plots represented 10 of the 12 ecozones in Canada that contain forests. The result of the work by Boudewyn et al. (2007) was about 270 unique sets of model parameters to convert stand-level volume to aboveground biomass components for over 60 tree species.

Biomass turnover and litterfall transfers

The CBM-CFS3 uses biomass turnover to represent mortality of biomass and litterfall rates to represent the transfer of the dead biomass to one or more DOM pools. Ecosystem processes represented by these parameters include tree, foliage, branch and root mortality. The model estimates biomass turnover using annual biomass turnover rates (% mortality yr^{-1}) for most stand development up until the point of natural stand break-up where yield curves decline. After this point, turnover from each biomass C pool is added to losses caused by stand break-up. After the CBM-CFS3 estimates biomass turnover, it uses litterfall transfer rates to assign the C to different DOM pools as specified in the model's structure (Table 5.2).

Table 5.2 Biomass turnover and litterfall transfer rates.

Carbon pools	Turnover rate (% C yr^{-1})	DOM receiving pool	Litterfall transfer rate (%)
Merchantable stem	0.45-0.67	Snag stem	100
Other wood	3-4	Snag branches	25
		AG fast	75
Foliage (SW)	5-15	AG very fast	100
Foliage (HW)	95	AG very fast	100
Fine roots	64.1	AG very fast	50
		BG very fast	50
Coarse roots	2	AG fast	50
		BG fast	50

Decay dynamics

Decomposition for every DOM pool is modelled using a temperature-dependent decay rate that determines the amount of organic matter that decomposes in a DOM pool every year. The CBM-CFS3 uses proportions to determine the amount of C in the decayed material that is released to the atmosphere (P_{atm}) or transferred to the more stable slow DOM pools (P_t). Slow DOM pools release all of their decayed material to the atmosphere. Decay dynamics are simulated in each annual time step (Table 5.3).

Table 5.3 DOM dynamic parameters in CBM-CFS 3.

Carbon pools	Decay parameters					Transfers	
	Base decay rate (yr^{-1})	Q_{10}	P_{atm}	P_t	Receiving pool	Transfer rate (yr^{-1})	Receiving transfer
Snag stem	0.0187	2	0.83	0.17	AG slow	0.032	Medium
Snag branch	0.0718	2	0.83	0.17	AG slow	0.10	AG fast
Medium	0.0374	2	0.83	0.17	AG slow	N/A	N/A
AG fast	0.1435	2	0.83	0.17	AG slow	N/A	N/A
AG very fast	0.355	2.65	0.83	0.17	AG slow	N/A	N/A
AG slow	0.015	2.65	0.815	0.185	AG slow	0.006	BG slow
BG fast	0.1435	2	1.0	0	N/A	N/A	N/A
BG very fast	0.5	2	0.83	0.17	BG slow	N/A	N/A
BG slow	0.0033	1	0.83	0.17	N/A	N/A	N/A

Representation of Disturbances

The CBM-CFS3 simulates natural and anthropogenic annual disturbances because these have been shown to significantly influence forest C dynamics (e.g. Kurz and Apps, 1999; Kurz et al., 2008a, 2008b). Disturbances are driven by available activity data such as forest health aerial surveys, harvested volume statistics or fire monitoring as provided by the user. There are four elements to disturbances in the model: controls, impacts, post-disturbance dynamics and land-use change accounting. Disturbance controls determine how the model selects stand types to be disturbed. Disturbance impacts are parameters that determine the transfer of C between pools or out of the ecosystem. Post-disturbance dynamics variables control the regeneration of the affected stand(s). Land-use change accounting affects the disturbance impacts, post-disturbance dynamics and the calculation of C stocks and fluxes when deforestation or afforestation occurs.

Disturbance controls

The CBM-CFS3 provides flexible disturbance control options to accommodate diverse activity data describing a wide variety of disturbance types. Control options include spatial criteria, stand characteristics, sorting of inventory, and targets. The spatial location of a disturbance event may be limited to a single spatial unit or a disturbance group-a collection of spatial units. The CBM-CFS3 can also use non-spatial stand characteristics defined in the inventory (e.g. species, age, amount of C in individual pools, and stand history) to select a list of stands eligible to be disturbed. For example, a salvage logging disturbance type can be set up with criteria that the stand was disturbed by fire within the previous five years. Likewise, multi-year insect outbreaks can be simulated with more severe impacts occurring only on stands with lighter infestations by the same insect in previous years. Once the list of eligible stands is established, the CBM-CFS3 sorts the stands.

There are 13 sorting algorithms, for example, random or highest amount of merchantable stemwood (Kull et al., 2006). Once sorted, the CBM-CFS3 then applies the disturbance target to the first stand in the list. Annual targets of the extent of forests affected by a disturbance event can be specified in three ways: as an area, as the amount of merchantable C, or as a proportion of all eligible stands. CBM-CFS3 applies the disturbance by stepping through all eligible stands and simulating the disturbance impacts until either (1) the target is achieved or (2) all stands in the eligibility list have been affected. Stands may be completely or partially affected by the disturbance. An efficiency variable controls the maximum proportion of a stand area affected, for example, to represent wetland buffers in harvest systems. This allows some control over the number of stands that will be disturbed in a given year. Note that the merchantable C target is applied to the pool that includes stemwood and bark. Therefore, harvest statistics (usually defined as volume without bark) must be increased to allow for the contribution of bark to achieving the target. The amount of area and C affected by a disturbance per time step are reported in the model output.

Disturbance impacts

In the CBM-CFS3, disturbance impacts are defined using a matrix that describes the proportion of C transferred between pools, as fluxes to the atmosphere, and as transfers to the forest products sector. The proportions are specific to each disturbance type and can vary spatially, to reflect spatial differences in disturbance intensity, e.g. fire (de Groot et al., 2007). The model includes a suite of default disturbance matrices or users can define their own using the graphical user interface. Disturbance matrices provide an efficient means to affect the large number of pools and fluxes of C. This flexibility allows for realistic modelling of management activities and natural disturbances.

Post-disturbance dynamics

To simulate stand succession rules and various management practices, the CBM-CFS3 framework includes flexible options to represent post-disturbance biomass dynamics. The biomass dynamics are influenced by the disturbance being either stand-replacing (age reset to zero) or causing partial mortality (age unchanged). In a stand-replacing disturbance, all merchantable trees are killed. The CBM-CFS3 sets the age to zero and assumes the stand starts re-growing on the same growth trajectory, unless given other instructions by the user. Transition rules provide the opportunity to simulate regeneration delays, planting or changes in species. Following a partial mortality event, the age of the stand and corresponding growth increments remain unchanged. This is an approximation that we could improve on with more field data quantifying post-disturbance growth response. Users can alter this assumption by defining transition rules. Transition rules provide flexibility for representing the post-disturbance dynamics of a forest stand. They specify the type of forest that would occupy the land area following a disturbance.

Land-use change accounting

Changes in land use are handled as disturbances in CBM-CFS3, but they have some unique characteristics. We added land-use change accounting to CBM-CFS3 because, globally, land-use change accounts for 20% of anthropogenic emissions of GHGs (Denman et al., 2007). The effects of land-use change can be both positive and negative. The clearing of forests to make way for another land-use such as agriculture or settlements – referred to as deforestation – results in increased emissions to the atmosphere (IPCC, 2003). The creation of new forests, through tree-planting on non-forested lands, referred to as afforestation or reforestation, can sequester additional C from the atmosphere. To account for the contribution of land-use change to the global C balance, the UNFCCC and Kyoto Protocol distinguish emissions and removals of GHGs on lands that have been subject to a continuous (>20 years) land-use, such as forestry or agriculture, from those that occur on lands that have recently undergone a change in land use, e.g. a conversion of forests to non-forest land-use, or vice versa.

Model Outputs and Indicators

The CBM-CFS3 provides a number of outputs that can be used to evaluate C stocks and stock changes, GHG emissions and to evaluate other forest indicators of interest for reporting or model validation purposes. At the end of each year the model reports C stocks and fluxes. The CBM-CFS3 reports the annual C transfers between pools, emissions to the atmosphere, and transfers to the forest products sector for each pool, summarized by classifier set and land-use class. Transfers and emissions associated with different disturbance types are reported separately so that the direct impacts of different disturbance types can be evaluated. Indirect impacts, however, cannot all be reported separately in the model output. For example, the direct emissions of C into the atmosphere and the transfers of C from living to DOM pools as a result of fire are reported by the model, but the subsequent release of C from decay of fire-killed biomass is not reported separately from the release of C from decay of other DOM and soil pools on site.

We frequently use the CBM-CFS3 outputs reporting the annual stock change for a pool and for the total ecosystem. The annual stock change for a biomass pool is effectively the net growth increment minus the losses. The annual stock change for a given DOM pool is the increase due to transfers into the pool (due to biomass turnover, decay dynamics or disturbances) minus the losses due to decay dynamics or disturbances. The sum of the stock change of all pools is the total ecosystem stock change. It indicates the annual net ecosystem C flux. Because this is a forest-based model, the sign convention on the output is negative for losses from the ecosystem and positive for accumulation within the ecosystem. The CBM-CFS3 reports GHG fluxes between the atmosphere and the forest lands, as well as those associated with land-use changes. The GHG estimate is reported as carbon dioxide equivalents (CO_{2e}). It includes emissions and removals of CO_2, and additional emissions of CH_4, N_2O, and CO due to wildfires multiplied by their global warming potential as appropriate for reporting under the Kyoto Protocol (IPCC, 1997). For all disturbances that involve burning, 90% of the C losses from burned organic matter goes into CO_2 emissions, the remainder being emitted as CH_4 (1%) and CO (9%).

CBM-CFS3 Application in BC Pilot

Carbon indicators

The carbon indicators should reflect carbon storage capacity, namely carbon pool sizes, and carbon fluxes, the capability of carbon exchange with the atmosphere. The standard carbon pools identified by International Panel for Climate Change (IPCC, 1996) for Land Use Land Use Change and Forestry (LULUCF) were aboveground biomass (AGBio), belowground biomass (BGBio), dead organic matter (DOM), forest floor litter, and soil. Although the flux indicators were varied according to the region and preferences of researchers, the indicators, such as net primary productivity (NPP), autotrophic respiration (Rh), and net ecosystem production (NEP), were commonly used by majority researchers for general communications. Normally, a forest ecosystem after a stand replacing disturbance (i.e., timber harvesting), the ecosystem is a net carbon sources (NEP <0), after a decade or two, the regeneration stands offset the autotrophic respiration, the ecosystem turns into a net carbon sink (NEP >0), as stands mature, the net ecosystem production decreases (Figure 5.4).

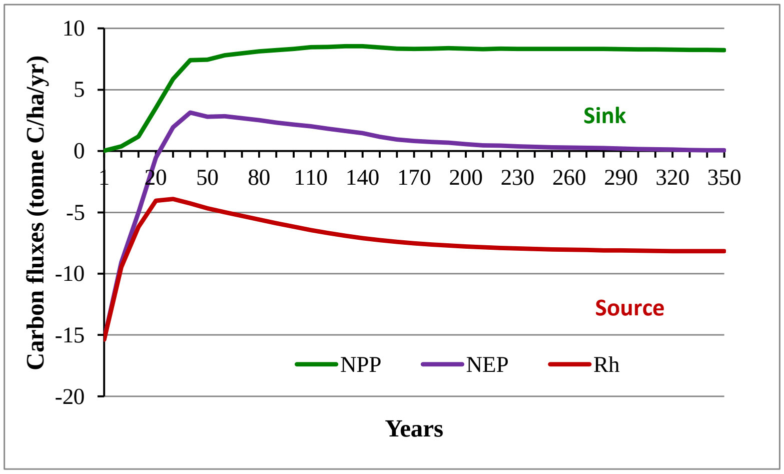

Figure 5.4 A disturbed forest ecosystem carbon dynamics.

Carbon curves

I took the concept of standing timber volume growth and yield by producing the major carbon pool curves (Figure 5.5). These curves can be further used in strategic modelling framework, or trade off analyses in order to optimize total ecosystem carbon or any component of carbon pools. These major carbon pools are required by IPCC and United Nations Framework Convention for Climate Change (UNFCCC) for reporting countries to fulfill Kyoto Protocol obligations.

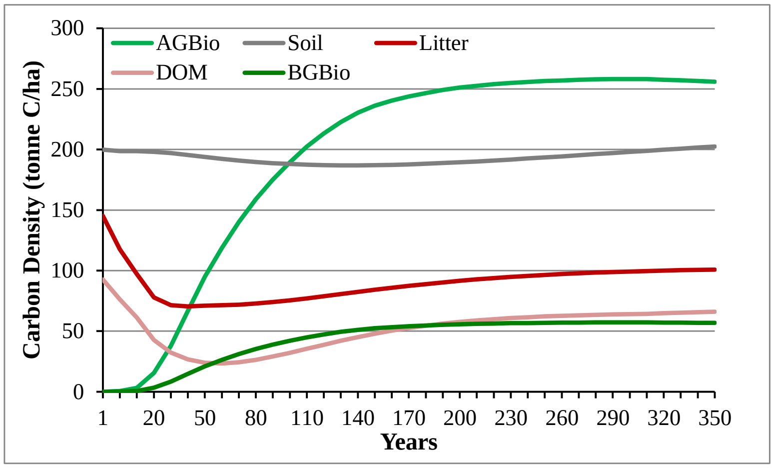

Figure 5.5 Five major carbon pool curves including above ground biomass (AGBio), soil, forest floor litter (Litter), dead organic matter (DOM), and below ground biomass (BGBio).

Carbon density under current growth conditions without disturbances. As one example to use carbon curves to project future forest ecosystem total carbon distribution (Figure 5.6). The Pitt River watershed total ecosystem carbon density at the year of 2012 (Figure 5.6a), 2020 (Figure 5.6b), 2050 (Figure 5.6c), and 2100 (Figure 5.6d). Since there are no disturbances (i.e., timber harvesting, wildfires, insects, etc), the carbon density increases across the landscape (from lighter green to darker green Figure 5.6a-d).

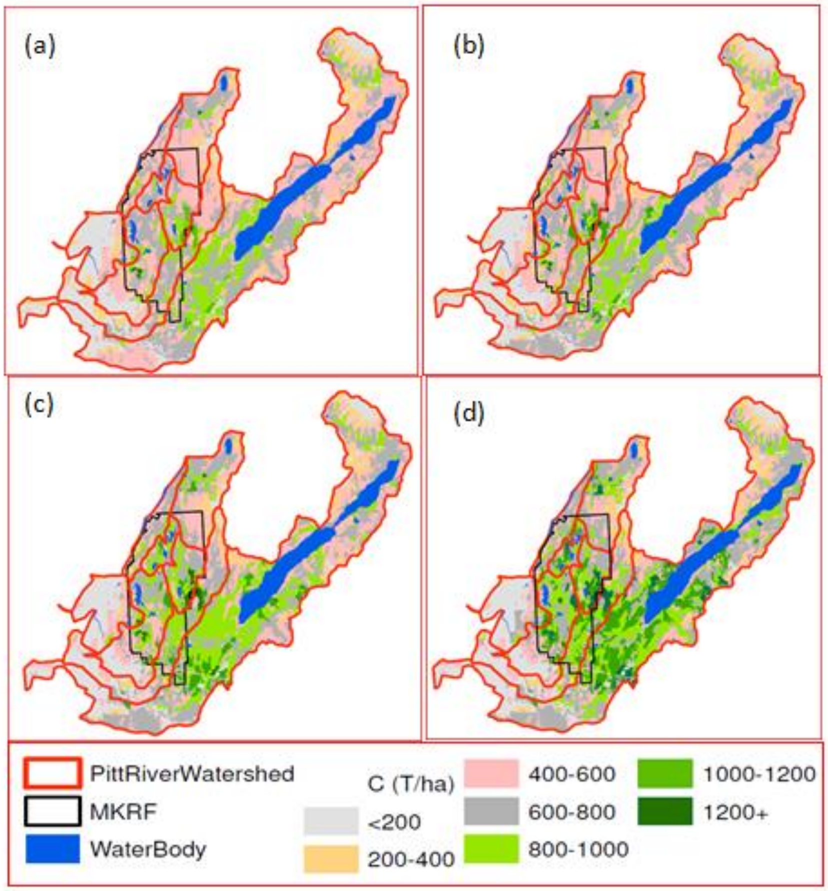

Figure 5.6 Carbon density distribution at year 2012 (a), 2020 (b), 2050 (c), and 2100(d).

Sustainable timber harvesting under current climate change

Carbon pool indicators under current management regime: the current management regime and harvest flow it reasonable choice from the carbon perspective (Figure 5.7). For example, the live biomass components (AGBio-green line and BDBio-light green) are relative stable over the analysis period, as expected that the dead organic matter decreases due to coastal climate. The historical harvests (solid blue line) fluctuated greatly, and peaked from year 2002 to 2004, reached over 25,000 tonnes carbon extracted from the ecosystem, and plunged down, due to economic down turn. For the given landscape, the sustainable flow of over 10,000 tonnes merchantable carbon can be extracted every year.

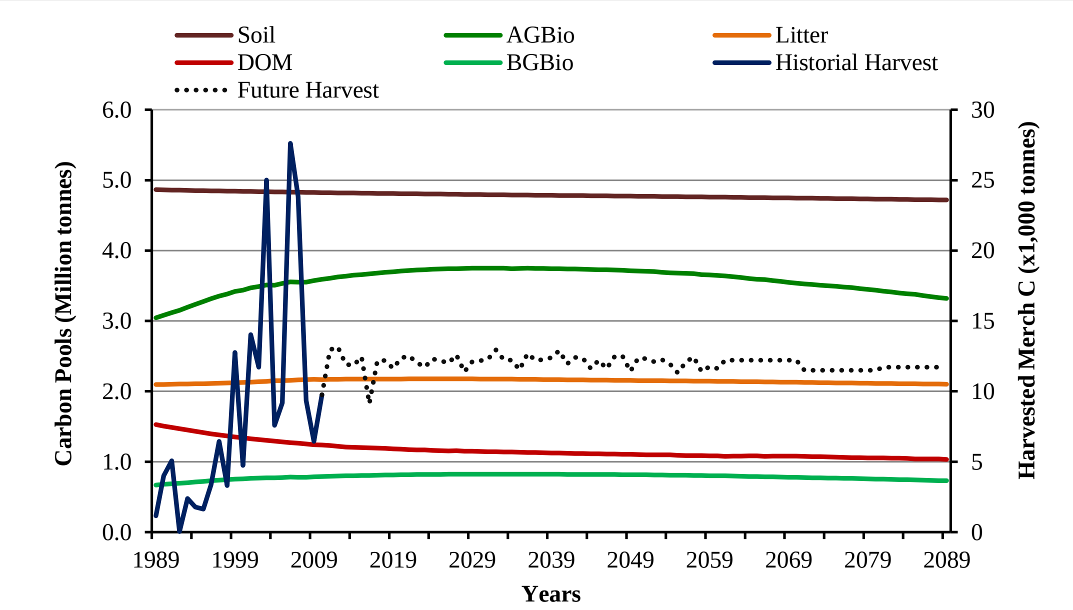

Figure 5.7 The major carbon indictors (fist Y axis) and harvest activities (secondary Y axis). Solid blue line represents the historical harvest activities, while the dotted blue line represents the management forecast.

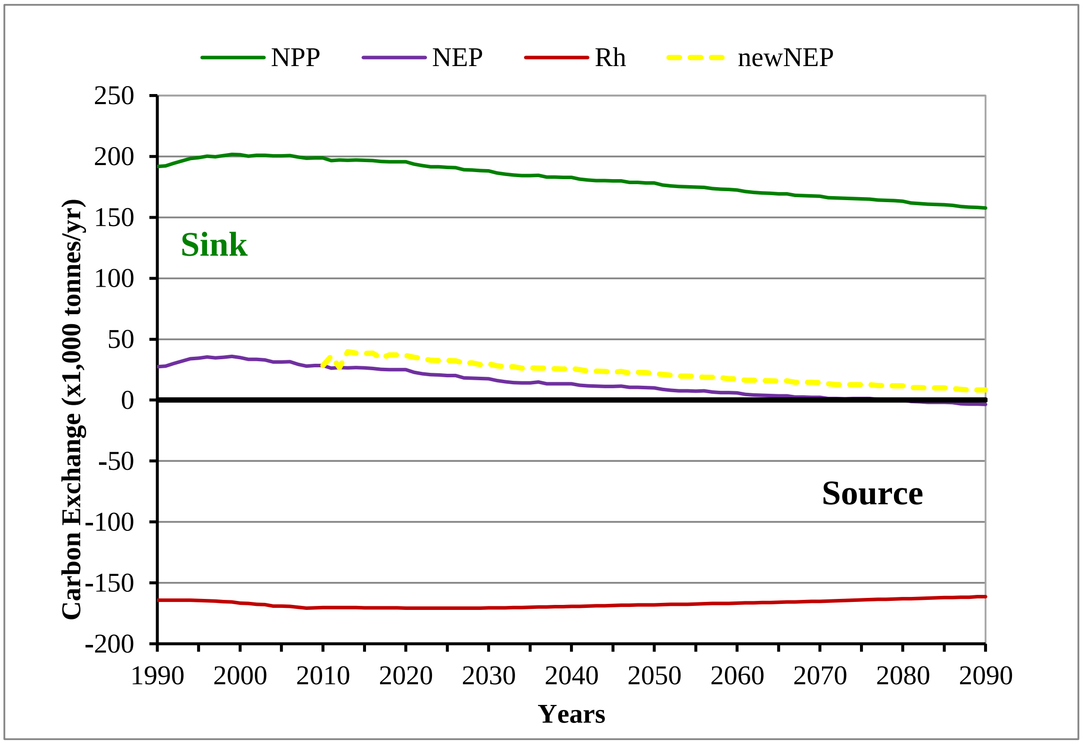

Figure 5.8 Major carbon flux indicators in the Pitt River watershed (NPP: net primary production; NEP: net ecosystem production; Rh: heterotrophic ecosystem respiration)

Carbon fluxes: the Pitt River watershed will be a net carbon sink (gaining carbon from atmosphere through photosynthesis) over the analysis horizon under the current UNFCCC Kyoto Protocol Accounting (magenta line, Figure 5.8). The landscape level net primary production is declining over the time. There are two factors contribute to this decline, one is the area of non-timber harvest landbase (NTHLB) is much larger than the timber harvest landbase (THLB). The over ecosystem performance (productivity) reflects the characteristic of NTHLB. Furthermore, the age structure in the NTHLB is older than that of THLB. For example, the average stand age at 2050 was 140 and 90 years old for NTHLB and THLB, respectively.

Since the new international negotiation after Durban (2012), the new accounting rules may change, especially for Canada, Russia, and Europe. Those countries advocated hard on the accounting rules for the harvest wood product (HWP) and looking forward baseline for LULUCF sector. For example, current Kyoto Protocol treated HWP as immediate on-site oxidation (also known as emissions), thus, in the accounting balance sheet, the wood products were treated as 'penalty' by unfair accounting rules. If the HWP is accounted as sources or sinks of greenhouse gas emissions, it really enhanced human activities when facing alternative resource utilization choices. The HWP accounted back to net ecosystem production (yellow dotted line), it increases the ecosystem overall performance. This rule change will have great implication of HWP in society as a whole. The second accounting rule change also has implications in this case study. As the Pitt River watershed inherited the age legacy due to less frequent wildfire stand replacing disturbances, the stand age is very old, especially for the NTLB stand. The stand growth tends to slow or stabilized at maturity. The major species at the study area are mature around 90-100 years old. As stands get older, the stands are suspected to insects attack, diseases infestation, and wildfire, especially the climate change caused environmental stresses (Figure 5.8).

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Chapter 6. Landscape Dynamics

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Introduction

LANDIS-II (LANdscape, DIsturbances, Succession) model is a spatial explicit landscape eco-model simulating forest succession and seed dispersal under different natural (e.g., fire, climate change) and anthropogenic disturbances (e.g., harvesting) across the landscapes (Mladenoff 2004, Scheller et al. 2007, Scheller et al. 2012). Figure 6.1 illustrates the cconceptual operating framework for LANDIS-II minus the biological disturbance, drought and biomass modules and biomass outputs. These elements represent additional modules that fit within this framework but do not change its structure.

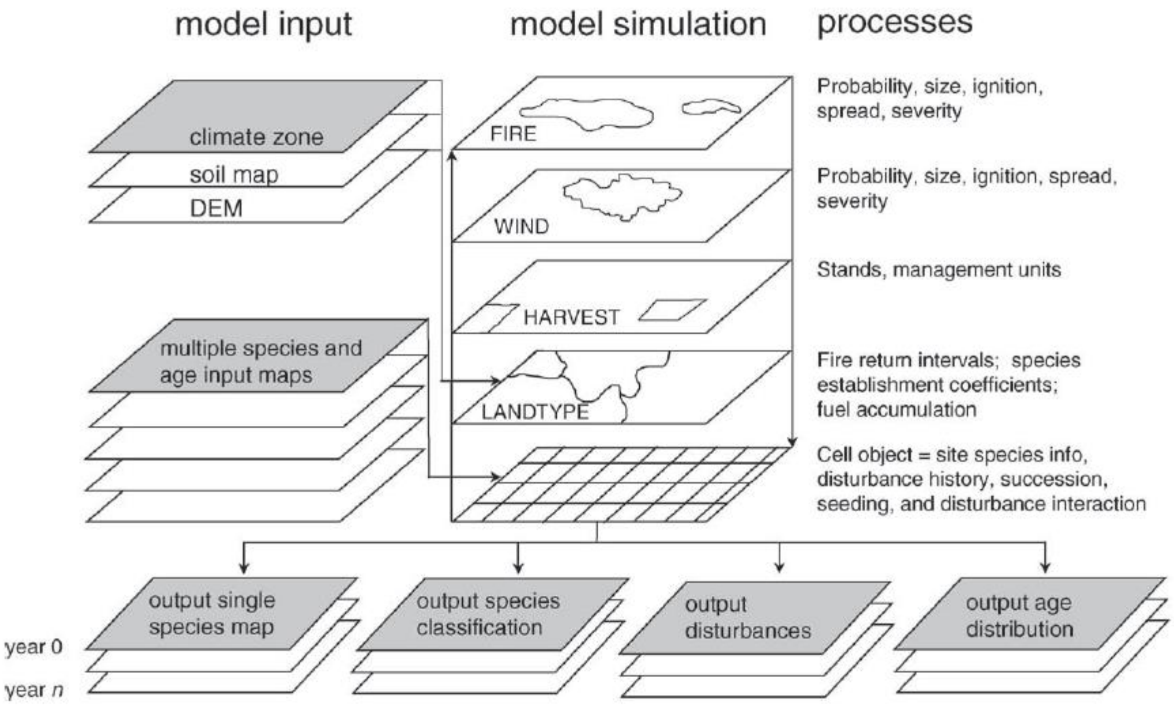


Figure 6.1 Conceptual operating framework for LANDIS-II (adapted from Mladenoff 2004)

Model Parameterisation

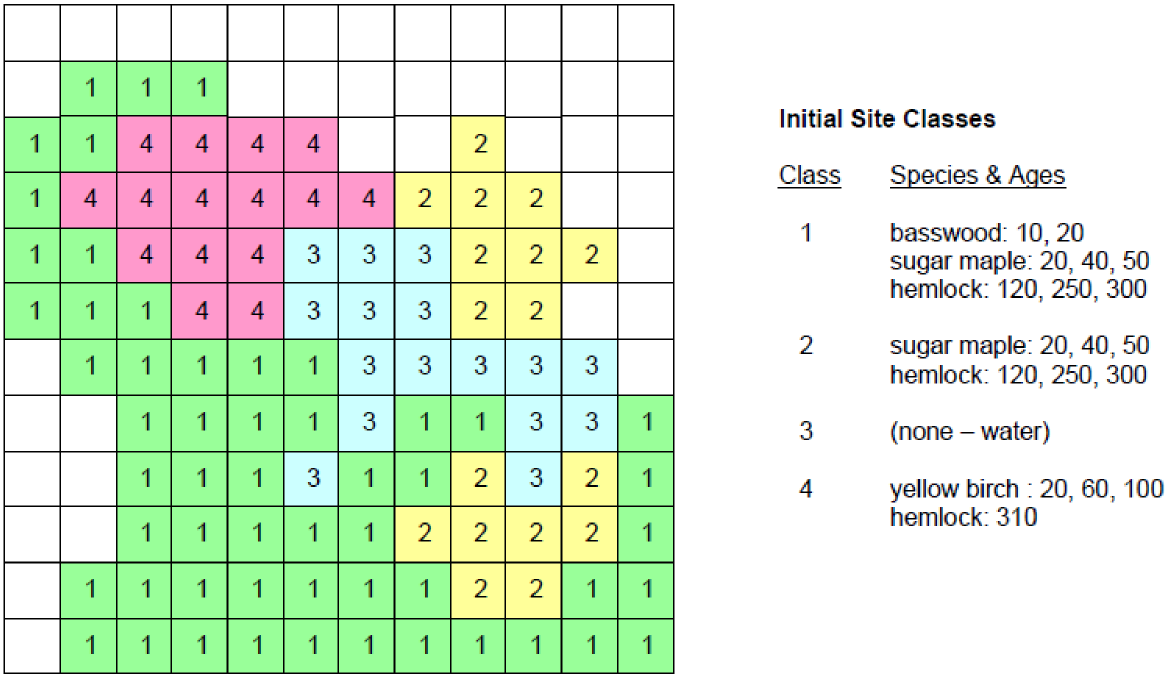
The parameterisation of LANDIS-II involves four main processes: (1) the classification of the landscape into "ecoregions"; (2) the classification of the landscape into initial communities based on species composition and stand age; (3) the parameterisation of species establishment and productivity; and, (4) the parameterisation of disturbance regimes such as fire. The following descriptions and steps are based on Scheller and Domingo (2011). Extensive documentation on all components of LANDIS-II can be found at http://www.landis-ii.org/.

Resolution

User defines spatial and temporal resolution. One hectare and 10 years are the common steps but the model can be run at finer resolutions and on one year time steps if desired.

Ecoregions

The landscape in question needs to be divided into into ecologically defined land types which are known as **ecoregions** in LANDIS-II. Ecoregions should represent Sites with similar ecological conditions such as climate and soil characteristics as these factors are likely to be the key underlying factors that drive ecological processes such as succession and disturbance. Two types of ecoregions are specified one for vegetation and one for fire regimes. For the former, ecoregion specific establishment coefficients and growth parameters can be assigned for each species. For the latter, ecoregion specific fire regimes can be assigned. Figure 6.2 and 6.3 provided illustrated examples of the spatial delineation of ecoregions on a landscape.



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		1	1	1	1	3	1	1	3	3	1
		1	1	1	3	1	1	2	3	2	1
		1	1	1	1	1	2	2	2	2	1
	1	1	1	1	1	1	1	2	2	1	1
	1	1	1	1	1	1	1	1	1	1	1

Initial Site Classes

Class	Species & Ages
1	basswood: 10, 20 sugar maple: 20, 40, 50 hemlock: 120, 250, 300
2	sugar maple: 20, 40, 50 hemlock: 120, 250, 300
3	(none – water)
4	yellow birch : 20, 60, 100 hemlock: 310

Figure 6.2 Ecoregion and initial community example (adapted from Scheller and Domingo 2011).

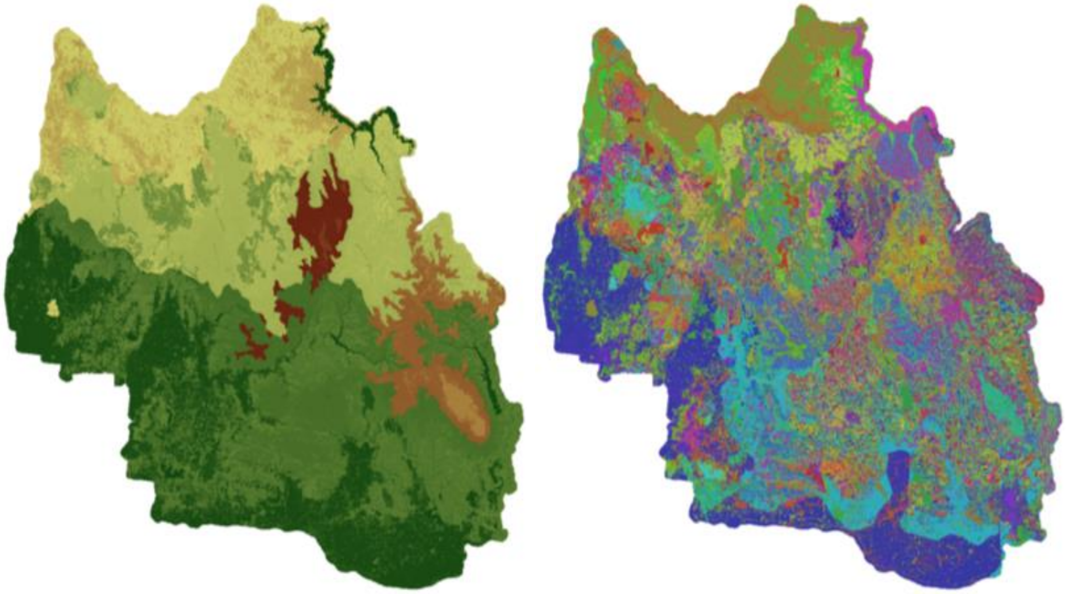

Figure 6.3 Ecoregions (right) and initial communities (left) used in the LANDIS-II modelling for the Australian case study. Ecoregions are a combination of macro (bioregion) and meso-scale(ecological vegetation classes (EVC)) associations between climatic, soil and vegetative communities. In this dataset there are 13 bioregions and 2349 initial communities.

Initial Communities

Initial communities that represent the current composition and age class structure of the landscape also need to be defined. Figure 6.3illustrates examples of initial communities. In areas with simple forest structure and age classes and high quality forest inventory this process can be straight forward. Where high complexity exists and forest inventory is coarse or incomplete, as was the case for the landscape in Figure 6.3, then this process may be more tedious and time consuming.

Species Parameters

The model uses life history parameters that vary among tree species. Individual disturbance processes may require additional species-specific parameters which are described in the documents about those disturbance modules (Scheller and Domingo 2011). The key species parameters, which are fixed, are: species name, longevity, sexual maturity, shade tolerance, fire tolerance, seed dispersal (effective and maximum distance), resprouting probability (minimum and maximum age of resprouting) and post-fire regeneration strategy (resprouting, serotiny, seed). In addition to these parameters species establishment and productivity parameters need to be specified for each species in each ecoregion. The user has a choice between age based and biomass based succession, if the former is used then establishment coefficients are the only parameters necessary and these parameters are fixed for the entire length of the simulation. If biomass succession is used then other parameters are required. The key parameters for biomass succession are establishment coefficients (probability of seed based establishment), maximum annual net primary productivity (MaxANPP) (g/m^2) and maximum biomass (g/m^2) within each ecoregion. Fixed biomass parameters are leaf longevity, woody decay rate, leaf lignin content and parameters that define the age when age-based mortality occurs and functions that define the age at which MaxANPP is achieved. Ecoregion AET must also be defined as does shade tolerance classes as a proportion of biomass must be defined. A key attribute of the Biomass succession model is the ability to change establishment coefficients and maximum annual net primary productivity and maximum biomass parameters in time to represent climate change.

Disturbances

LANDIS-II allows for the modelling of fire, wind, drought, and biological disturbances such as insect defoliation. There are two fire modules: area based and weather based. For each module the user must delineate the landscape into fire ecoregions. Figure 4 illustrates and example of a landscape classified into fire ecoregions. In the former module (see Scheller and Domingo 2012) the user must specify mean fire size, minimum fire size, maximum fire size, ignition probability and a fire spread parameter, “K” that determines the probability of a fire spreading into a cell given the age of the forest in the cell for each fire ecoregion. The “K” value is usually set to the mean fire return interval for a fir ecoregion. In the weather base module fire weather parameters based on the Canadian Fire weather and fuel prediction model are required. This module is very detailed and I suggest reading Sturtevant et al. (2009, 2010) to get a detailed overview of this module. Both modules allow the user to change fire regime characteristics to reflect climate change in time and space.

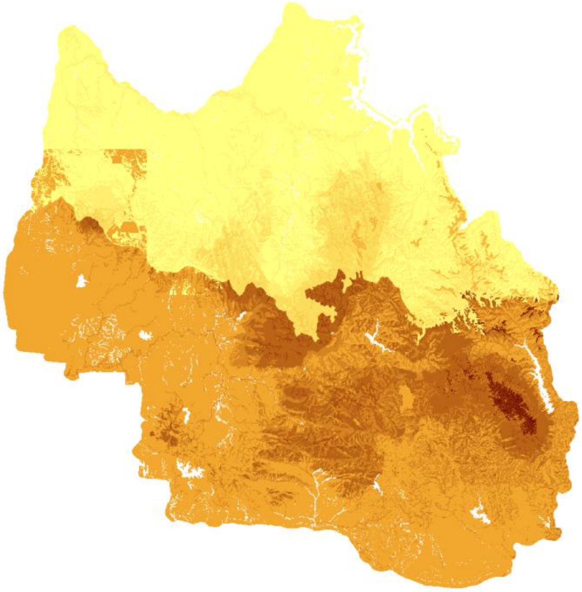

Figure 6.4 Maps of the fire ecoregions used in the LANDIS-II modelling. Each fire ecoregion has specific fire regime attributes (mean fire size, maximum fire size, fire return interval). Fire parameters are dynamically changed at user defined time steps.

Biological disturbances are modelled using the BDA module developed by Sturtevant et al. (2004; 2008). In this module the user needs to define the outbreak characteristics of a biological agent. These parameters include information on the temporal patterns of outbreaks (i.e. return intervals) and intensity of outbreaks (i.e. no to intense outbreak). The dispersal ability of the agent must also be defined to propagate the agent through the landscape following once an outbreak has been initiated. Disturbance modifiers that modify the habitat suitability for an agent, for example wind and bark beetles, can also be provided if required. The final parameter required is to define the species and their age classes that are susceptible. Wind disturbances require parameters that define the minimum, maximum and mean event sizes and the return interval for each ecoregion and the probability of mortality for different age classes within stands (see Scheller and Domingo 2007).

Management

Within LANDIS-II management prescriptions are based on the application of forest harvesting and silviculture prescriptions. At the broadest scale, the landscape is divided into management units which define collections of stands to which specific harvesting prescriptions are applied (Scheller and Domingo 2008; Scheller et al. 2010). Figure 5 illustrates how management units can be delineated using ArcGIS and land use and zoning maps. Stands are collections of cells that represent typical forest management block sizes. A series of silviculture prescriptions may be defined to each management unit to specify the silviculture that is to be undertaken. Prescriptions can be shared across management units and determine how stands qualify for harvest, how they are ranked to determine the order in which they are harvested, how sites within stands are selected for harvest, and the species and ages classes that are to be removed from those sites. For details on harvesting see Scheller and Domingo (2008 and Scheller et al. (2010). The user can apply the following silvicultural approaches:

- Clearfelling
- Seed tree
- Shelterwood
- Patch cutting
- Group selection
- Selection
- Thinning from above
- Thinning from below

For the latter three approaches, specific species and age classes can be targeted by the user. The User must also indicate whether a species should be planted after harvesting. If planting is not specified then natural regeneration is utilised. The user may also specify specific forest types that are to be protected or given priority for harvesting based on species and or age.

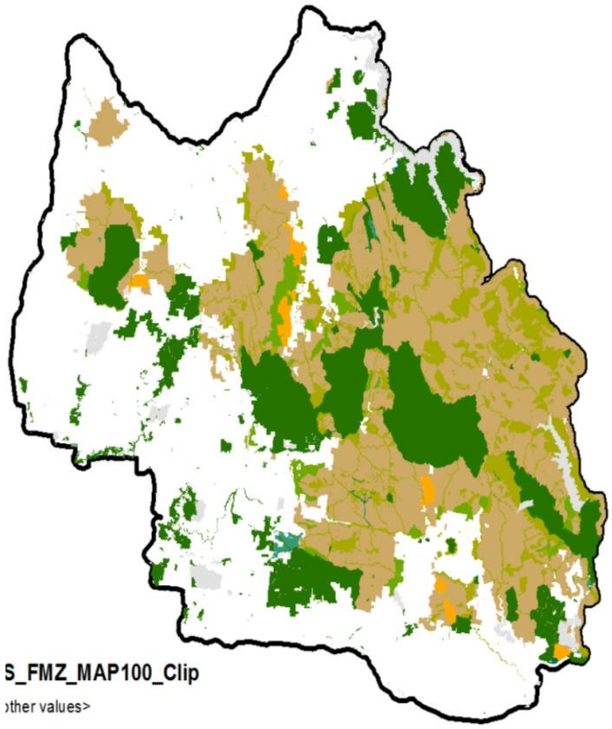

Figure 6.5 Maps of the management units used in the LANDIS-II modelling for SE Australia. Dark green patches are parks with no harvesting, white is farmland, grey is reservoirs, orange are pine plantations, other greens are special management zones with no harvesting but planning burning and the beige are state forests open for timber harvesting and fire management.

Application

To illustrate the utility and strength of using LANDIS-II to model the impacts of forest dynamics and example is provided in Figure 6.6. Analysing the model outputs in GIS allows for spatial chronosequences of changes in species distribution or forest types to be illustrated and analysed. The model outputs include area and volume harvested, area burned by severity class, area impacted by biological disturbances, species presence and absence, species abundance as a function of biomass, tree ages, stand ages and user defined forest types. The example provided in Figure 6.6 shows the response of forest types over 150 years of climate change with the occurrence of wildfires. The impacts of alternative forest management strategies that facilitate adaptation to climate change can be modelled using LANDIS-II and then compared to the outcomes from these baseline scenarios to assess the extent and type of management required to reduce the loss of key forest types.

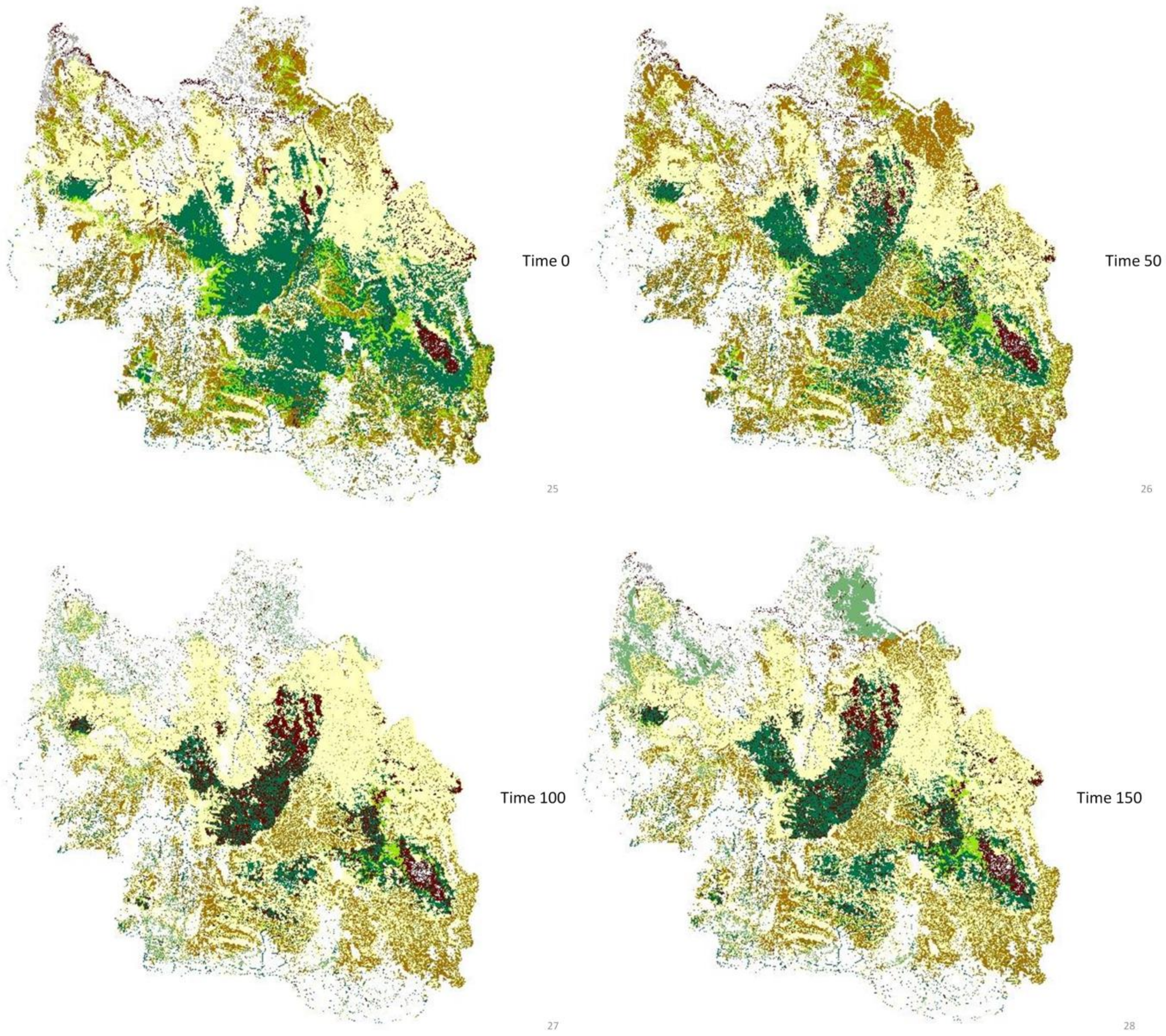

Figure 6.6 Output from LANDIS-II model for the Central Highlands Forest Management Area in Southeast Australia. The dark green represents wet eucalypt forest dominated by Eucalyptus regnans, the most commercially valuable and important tree species for the forest industry and an important forest type for many arboreal mammals and forest owls. This forest type is also an important forest type in the City of Melbourne's water catchments.

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Chapter 7. Climate Niche Modelling for Ecosystems and Species

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Bioclimate Envelope Modelling for Ecosystems

Ecological land classification systems are often used for natural resource management, such as in British Columbia (BC), Canada. The ecosystem classification system is called Biogeoclimatic Ecosystem Classification (BEC) (Meidinger and Pojar 1991). It divides the province into 16 ecological zones that reflect terrestrial ecosystem differences along large-scale climate gradients related to changes in altitude, latitude and continentality (Figure 7.1a). These zones are subdivided into increasingly smaller units called subzones and subzone-variants, reflecting plant community composition and structure differences along finer-scale climate gradients. These ecological units are widely used for resource management planning and decision-making in BC.

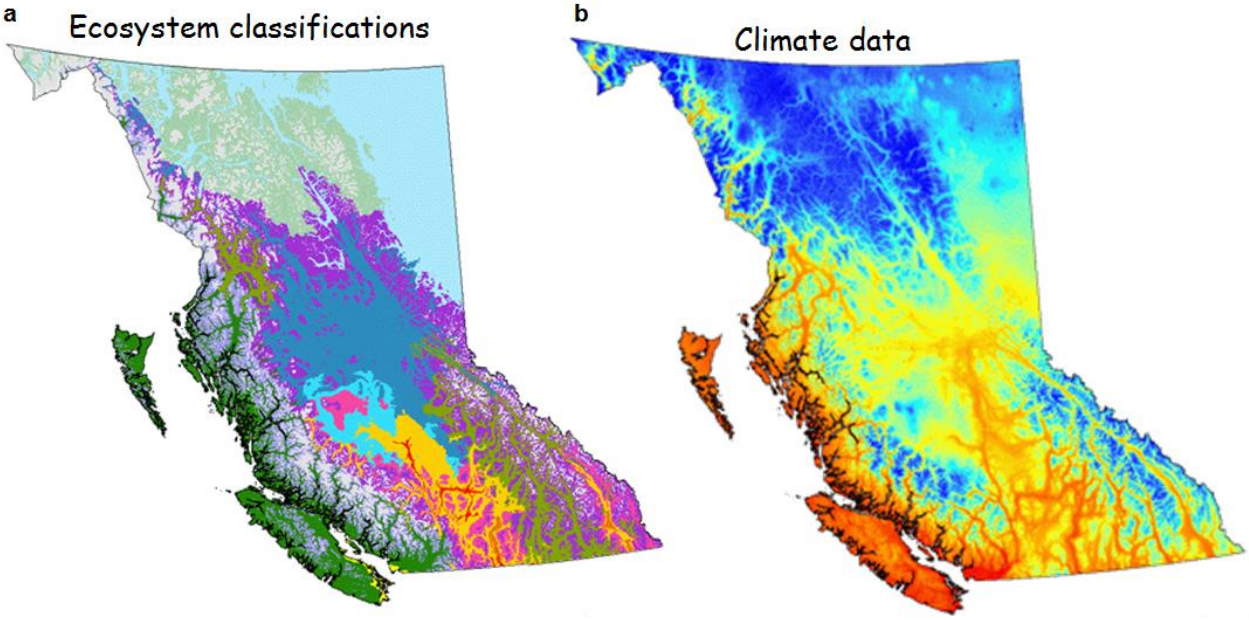

Figure 7.1 Maps of BC ecosystem classifications (a) and spatial climate data (mean annual temperature)(b).

Ecosystem data

The digital map of the BEC system was rasterized to grid resolutions of 1600 m (370,205 cells) and 800 m (1,904,654 cells) in ArcGIS (version 9.2) for model building and model validation, respectively. Each grid was assigned to the ecosystem (i.e., zone, subzone, and subzone-variant) occurring at the center of each cell.

Climate data

ClimateWNA (version 4.6) (Wang et al. 2012b) was used to generate climate data. An input file containing point location coordinates (latitude, longitude, and elevation) for each rasterized grid cell was queried by ClimateWNA to generate 12 annual, 16 seasonal, and 48 monthly climate variables for each grid cell. The climate data were generated for: 1) the reference period (Figure 7.1b) to develop and validate our model, 2) the last decade (2001-2009) to assess the effects of recent climate change, and 3) three future periods (2020s, 2050s and 2080s) to project impacts of future climate change.

Model building

We used the R version (Liaw and Wiener 2002) of Breiman's (2001) of the Random Forests (RF) algorithm to model relationships between climate for the 1970s reference period and the geographic distribution of ecosystems in BC. RF produces many classification trees, collectively called a 'forest', and aggregates the results over all trees. Each of these decision trees in the forest is constructed using a bootstrap sample of the input data (i.e., a random sample with replacement) so that the resulting dataset ('bagged sample') contains about 64% of the original observations, and the remaining observations comprise the 'out-of-bag' (OOB) sample. Tree nodes (bifurcations in a branch) are created using the climate predictor variable that has the smallest classification error among a randomly selected subset of predictor variables. By default, the number of predictors randomly selected at each node is the square root of the total number of predictors. Using the trees grown with the bootstrap sample, each of the independent observations in the OOB sample is classified (assigned to an ecosystem) and a model prediction error, called the OOB error (% of incorrectly classed observations), is calculated.

To calibrate the model, we compared OOB prediction errors for models using four different sets of climate variables: 1) 12 annual variables, 2) 16 seasonal variables, 3) 48 monthly variables; and 4) all 76 climatic variables. The variable set with the lowest OOB error was used to build the model. The number of predictors selected at each node was optimized using the function *tuneRF*. RF was run with 200 classification trees; use of a larger number of these decision trees did not reduce OOB error. For the model that included all 76 climate variables, importance values (as determined by a decrease in Gini values, see Brieman 2001) generated by RF were used to reduce the number of climate variables included in the model without compromising model accuracy.

In Random Forest, each sample data point has the same contribution to the model. Therefore, the model is more weighted by the ecosystem classes with a large number of sample data points. A sampling strategy is often needed to balance the sample size among the ecosystem classes. The sampling strategy applied in this modelling process is described in Wang et al. (2012).

Model accuracy

The model predicted current ecosystem distributions with high accuracy at BGC zone, subzone (Figure 7.2) and variant levels. The predictions used independent dataset; the data points used to build the model were not used for the predictions.

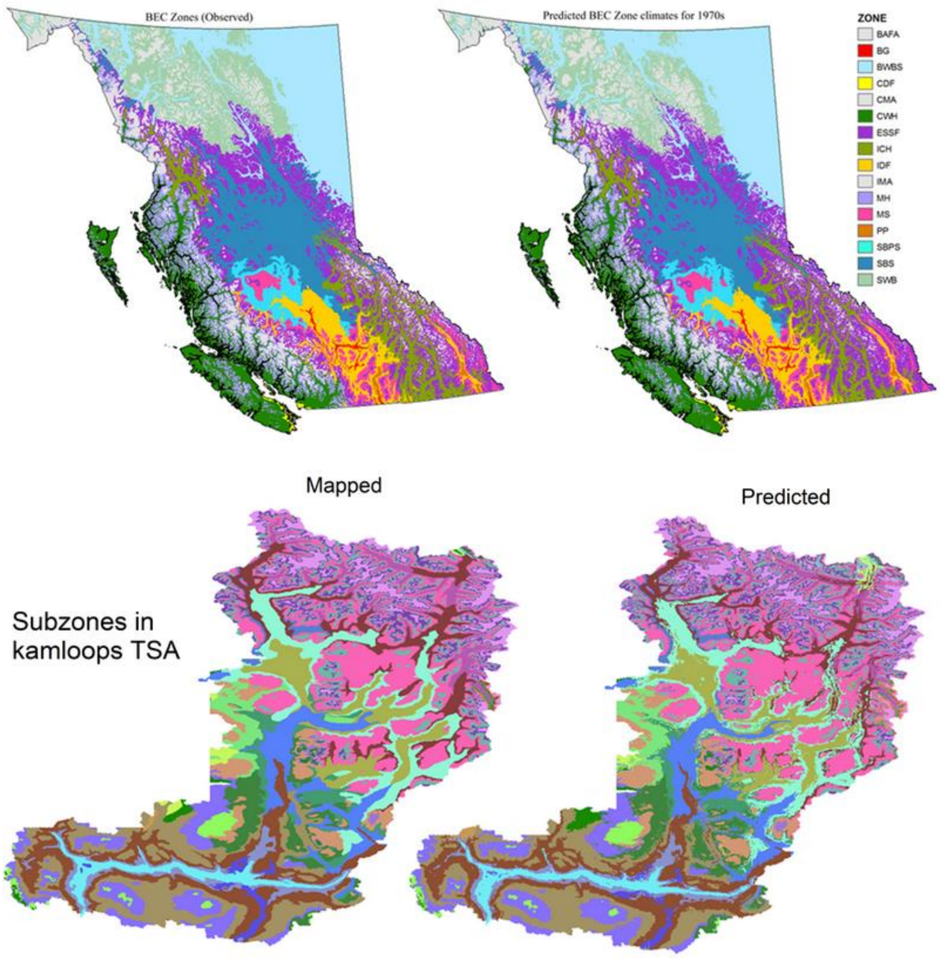

Figure 7.2 Comparisons between currently mapped ecosystems (left) and predicted ones (right) at BEC zone (upper) and subzone (lower) levels.

Variability among the projections using different climate change scenarios

Predicted climate changes from difference greenhouse gas emission scenarios and different General Circulation Models (GCMs) varied with a wide range. There are over 140 combinations of emission scenarios and GCMs, which were collectively called climate change scenarios. We chose 20 of them to represent the range and crowd (Figure 7.3).

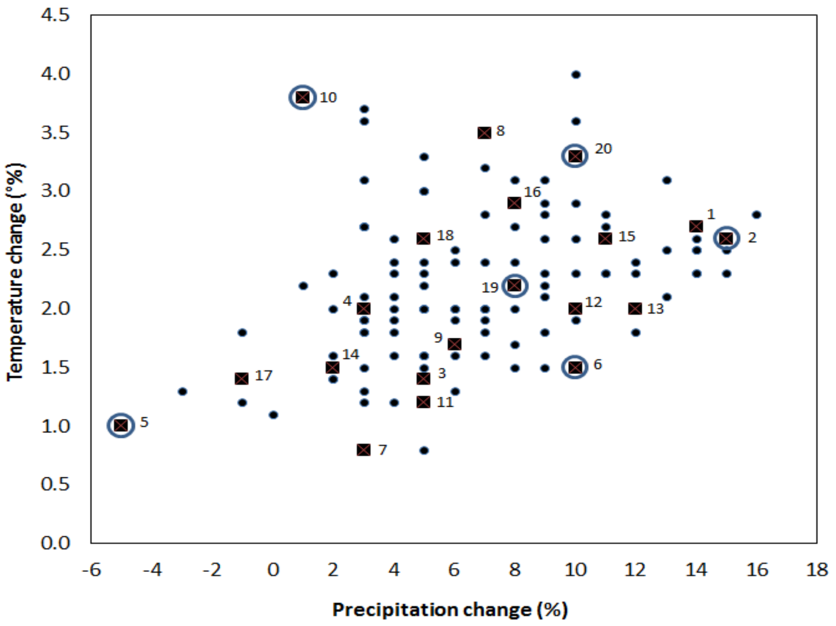

Figure 7.3 Predicted changes in temperature and precipitation for BC by 134 climate changes scenarios for 2050s.

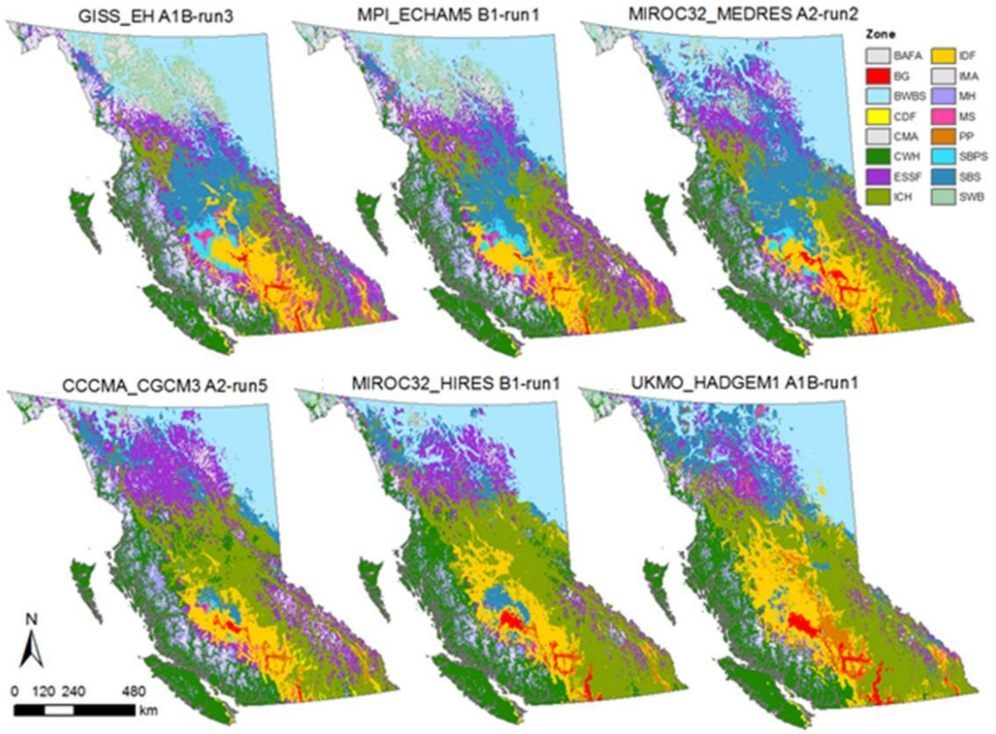

Figure 7.4 Differences in projections for 2050s using different climate change scenarios.

Projections for one future period (2050s) differed substantially depending on climate change scenarios used. The differences are shown using six climate change scenarios (Figure 7.4).

Consensus projections

A consensus projection for a future period was generated based on the most frequently projected ecosystem zone for each pixel among the 20 individual projections. We used the level of the model agreement among the 20 individual projections to represent the level of uncertainty (or consensus strength) of the ecosystem climate niches under climate change (Figure 7.5).

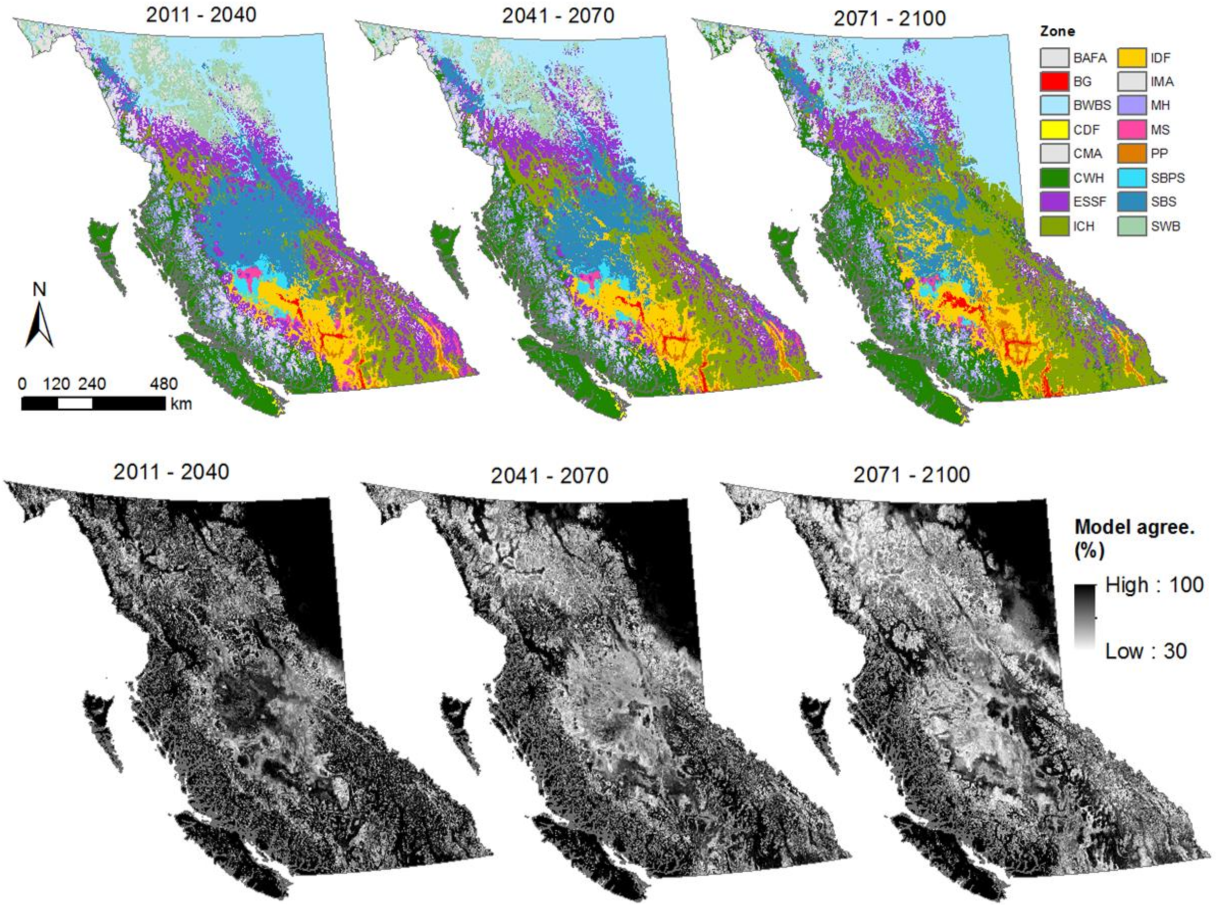

Figure 7.5 Consensus projections based 20 projections using different climate change scenarios. The upper maps show the projections, while the lower maps are the levels of the model agreement.

Variability in the impact of climate change on ecosystems

Impacts of climate change ecosystems differ considerably. The bioclimate envelopes of some ecosystems are projected to contract, while some others to expand (Figure 7.6). In BC, several spruce dominated ecosystems are projected to move upward and northward, and their suitable climate niches are going to decline. However, several productive forest ecotypes are projected to expand. Their dominant species include Douglas-fir, interior redcedar and western hemlock. These species are fast-growing and economically important species. Climate change would make more areas suitable for planting these species and potentially could increase the productivity in BC.

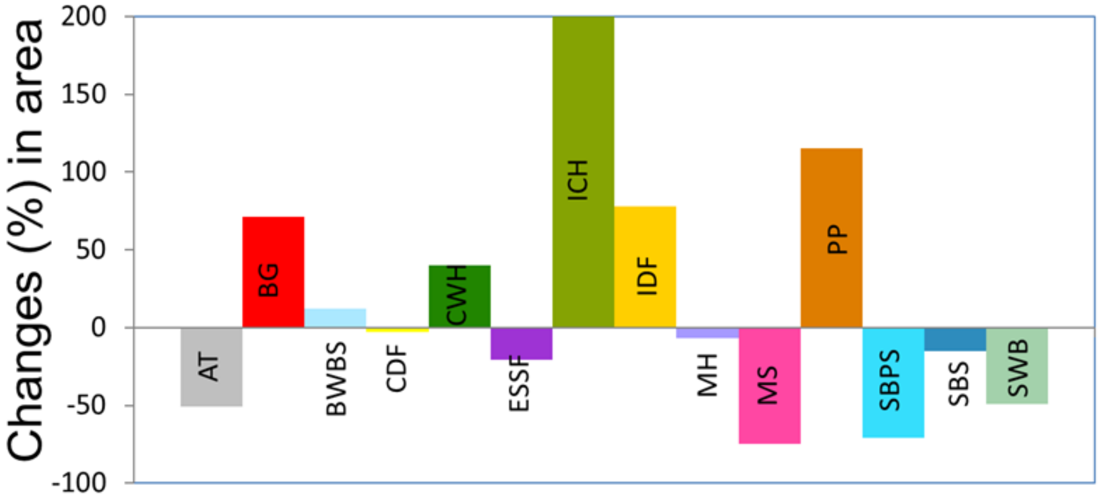

Figure 7.6 Projected changes in area for different forest ecosystems in BC. Climates suitable for Interior Cedar-Hemlock (ICH), Ponderosa Pine (PP), Interior Douglas-fir (IDF), Bunchgrass (BG) and Coastal Western Hemlock (CWH) zones are projected to expand. Meanwhile, Climates characterized for Montane Spruce (MS), Sub-Boreal Pine - Spruce (SBPS), Spruce - Willow - Birch (SWB) and Alpine Tundra (AT) zones are projected to contract.

Bioclimatic Modeling for Species

Ecosystem niche based modelling

Species bioclimate envelopes can be modeled by associating species distributions with ecosystem classes if such data are available. In British Columbia, we associated species frequencies with Biogeoclimatic subzone-variant (Wang et al. 2012a). After the bioclimate envelope of a subzone-variant was projected, the projection of the associated species was also achieved. Figure 7.7 shows the projections of the suitable climate niche for Douglas-fir in three future periods.

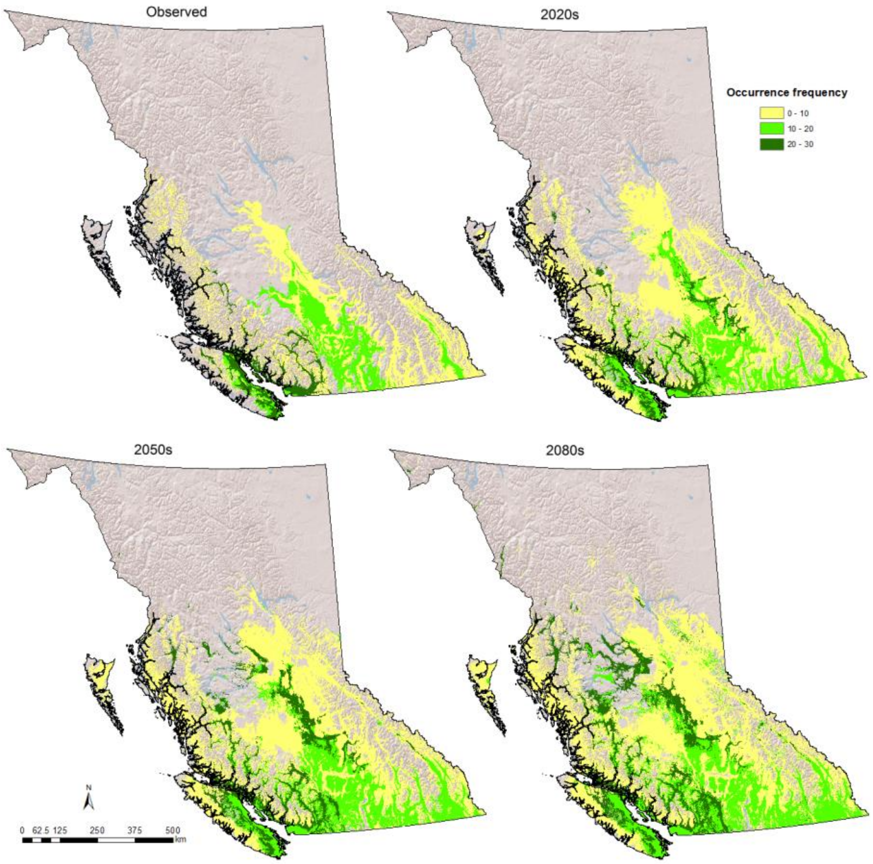

Figure 7.7 Projections of the bioclimate envelopes of Douglas-fir for 2020s, 2050s and 2080s based on consensus projections using 20 climate change scenarios.

Species present-absent data based modelling

If the present-absent data are available for a species, the same modelling approach used in modelling ecosystem classes can be used to model the bioclimate envelopes for individual species. However, to balance the sample sizes between present and absent categories is more critical in modelling for species than for ecosystems as the number of data points for the absent category is often much larger than that for the present category. By simply making the samples equal between these two categories do not work well in most cases because climate conditions in the areas for the *absent* category are more heterogeneous and need a larger sample to represent it. We applied a “multiple- forests” approach to solve this problem.

With the multiple-forests approach, a balanced sample dataset was constructed for each of 10 Random Forests. Among the 10 training datasets, the *present* data points were identical, but the data points for the *absent* data points were randomly sampled. Using this approach, balanced datasets satisfy the Random Forest requirements, while the repeated random sampling of the area for absent improves the representation of the heterogeneous climate conditions for this category. Predictions of the 10 Random Forest models were aggregated for the final model output.

We modeled Chinese Fir and Chinese pine using this approach. Climate variables for the reference period 1961-1990 and future periods were obtained for each data points in the training datasets using ClimateAP. For the future period, we used the A2 emission scenario from the Canadian third generation of Coupled Global Climate Model (CGCM3) for demonstration (Figure 7.8 and Figure 7.9). More climate change scenarios from the IPCC Fifth Assessments will be used later on.

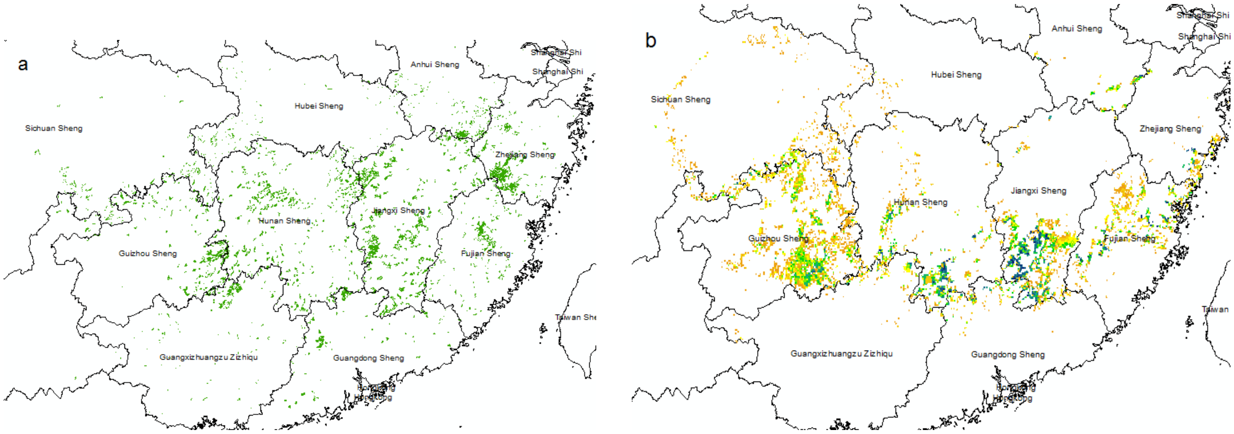

Figure 7.8 Projected shifts in climate niches for Chinese fir: a) current geographic distribution; b) projected climate niche suitable for this species in 2050s based CGCM3 A2 run4.

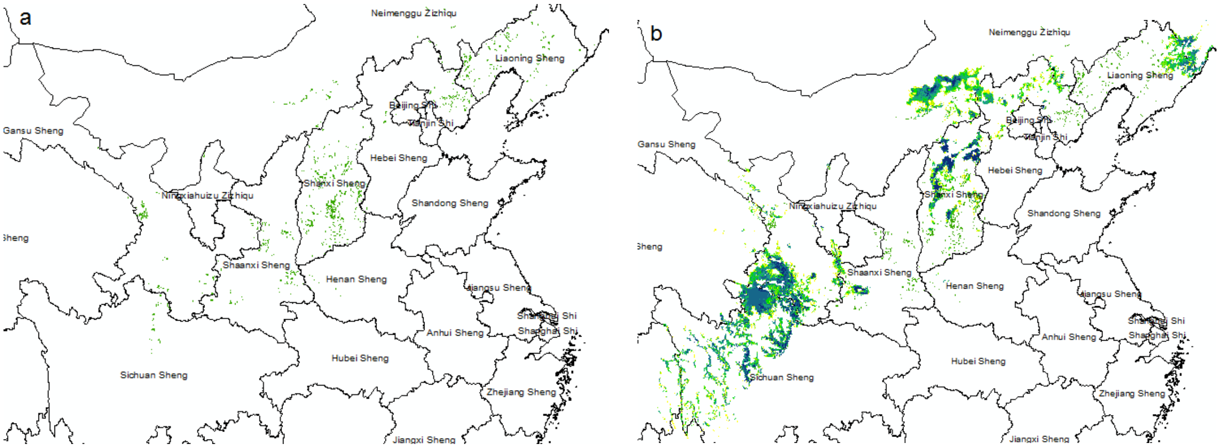

Figure 7.9 Projected shifts in climate niches for Chinese pine: a) current geographic distribution; b) projected climate niche suitable for this species in 2050s based CGCM3 A2 run4.

Modelling the Response of Tree Populations to Climate

Although tree species as a whole can be characterized by their bioclimatic envelopes, variation in response to climate among populations within a tree species is well recognized (Matyas 1994, Rehfeldt et al. 1999, Wang et al. 2006, Wang et al. 2010), and local adaptation of tree populations along climatic gradients has been demonstrated (Epperson 2003, Howe et al. 2003). For example, peripheral populations of lodgepole pine (Pinus contorta) from cold environments at the northern limit of its distribution grow much slower under favorable temperatures for this species than populations from central populations (Wang et al. 2006). This suggests that localized northern populations would be unable to take full advantage of warming temperatures attributed to climate change while some populations in the south are likely to be growing outside their bioclimatic envelopes (Rehfeldt et al. 1999, Wang et al. 2006). Therefore, climate change will also cause climate mismatches at the population level within a tree species.

Climate has long been recognized as playing a key role in both these determinants of phenotype in plants: in the short term, through direct effects on phenotypes via environmental effects on survival, growth, and reproduction and in the longer term, through acting as a major selection force affecting plant genotypes. Genetic and environmental effects of climate on phenotypes have previously been used to develop population transfer functions and population response functions using provenance test data for climate change studies.

A transfer function relates the performance of multiple populations to the climatic transfer distances between their provenances and a particular planting site (i.e., site climate minus provenance climate). A general transfer function (Rehfeldt et al. 1999) and climate response functions (Wang et al. 2006) for Lodgepole pine are shown in Figure 7.10.

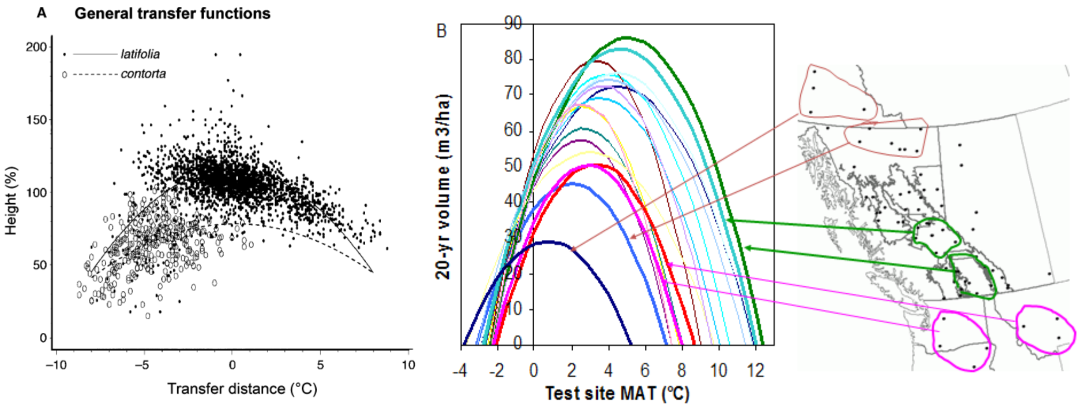

Figure 7.10 A general transfer function (Rehfeldt et al. 1999) and climate response functions (Wang et al. 2006) for Lodgepole pine.

Both transfer functions and response functions have limitations. By pooling data from multiple sites in developing a general transfer function, it is assumed that the shape and position of individual transfer functions are the same across different environments. However, this assumption is often not valid (Wang et al. 2010). Thus, individual transfer functions or genecology functions are developed to overcome this limitation. However, the genecology functions are test site specific (i.e., only valid for the specific test). Similarly, response functions are population specific; each response function is valid only for the specific population for which it is developed. Recently a new approach has been developed by integrating the genecology and response functions into a universal response function to overcome these limitations (Wang et al. 2010) (Figure 7.11).

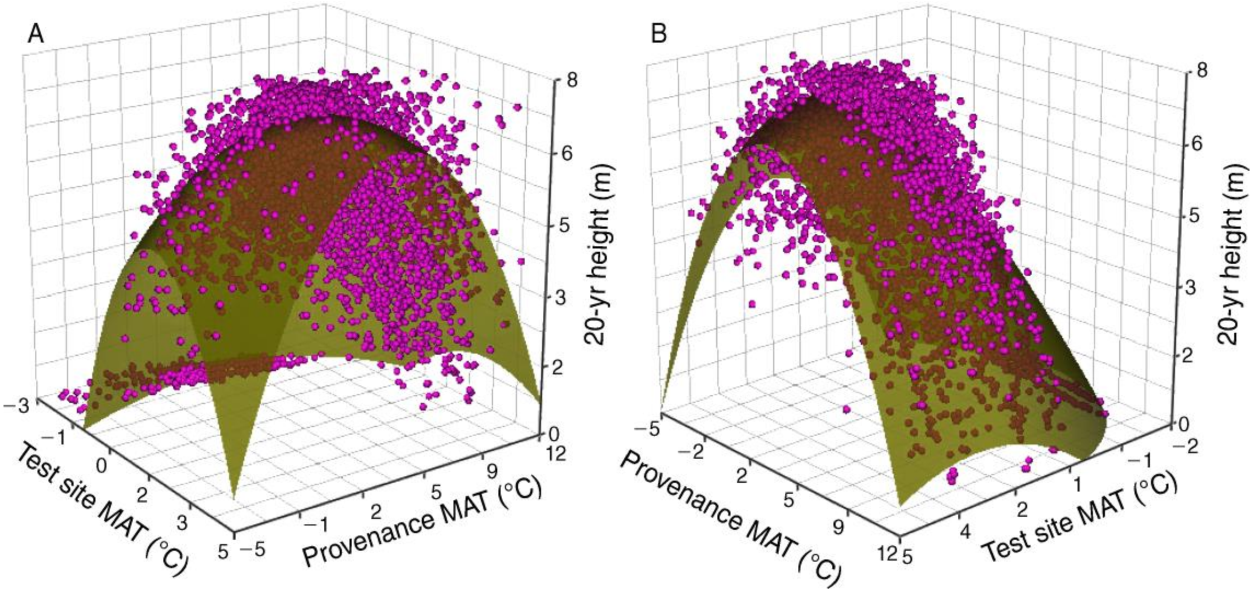

Figure 7.11 The universal response function for Lodgepole pine adopted from Wang et al. (2010).

The universal response function has the following advantages over the conventional transfer functions and response functions: (1) improve predictions of climate change impacts on phenotypes; (2) reduce the size and cost of future provenance trials without compromising predictive power; (3) more fully exploit existing, less comprehensive provenance tests; (4) quantify and compare environmental and genetic effects of climate on population performance; and (5) predict the performance of any population growing in any climate.

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Chapter 8. Modelling Climate Impacts on Forest Growth and Mortality

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ForWaDy: The Forest Hydrology Submodel Used in FORECAST Climate

ForWaDy (Forest Water Dynamics; Seely et al. 1997; Seely et al. 2006) is a vegetation-oriented, forest hydrology model. A diagram illustrating the model structure and function is shown in Figure 8.1. The model can be used as a stand-alone application, and it is integrated within FORECAST Climate where it is coupled to the main tree growth engine and the tree ring model (Seely and Welham 2010).

ForWaDy simulates potential evapotranspiration (PET) using an energy balance approach based on the Priestly-Taylor equation. Incoming radiation is partitioned among vertically stratified canopy layers (vegetation type) and the forest floor to drive actual evapotranspiration (AET) calculations. The model has a representation of soil physical properties dictating moisture availability, storage, and infiltration, and it simulates the relative impact of soil cover depth, minor vegetation competition and climate on the water availability for trees. A detailed description is provided in Seely et al. (1997, 2006).

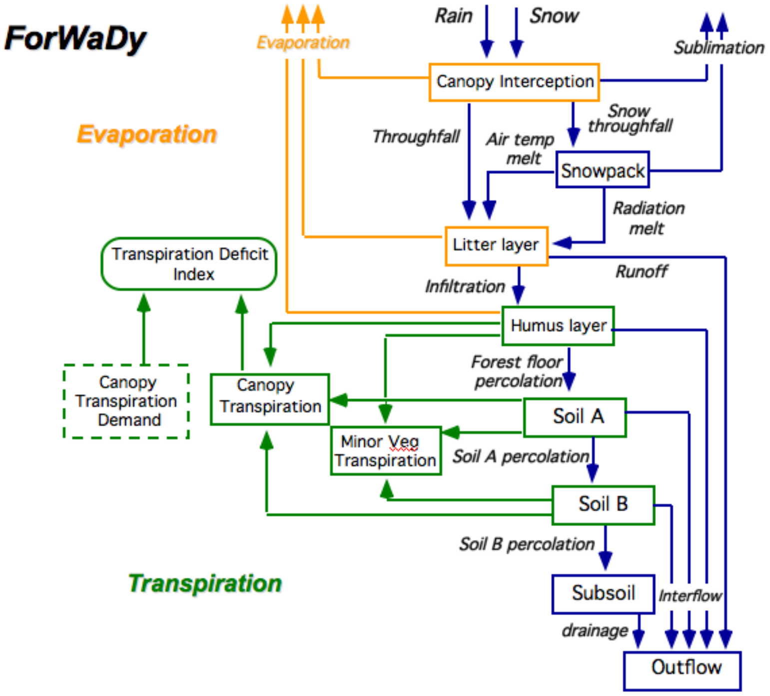

Figure 8.1 Schematic illustration of the structure of ForWaDy indicating the flow pathways and storage compartments represented in the model.

Water stress in ForWaDy is calculated as a transpiration deficit index (TDI). In essence, the TDI represents the difference between potential transpiration (as dictated by available energy) and actual transpiration (limited by available moisture), as follows:

TDI = (CanT_Total - CanTActual)/CanT_Total

where:

CanT_Total = energy limited transpiration: f (leaf area index, intercepted short-wave radiation, canopy albedo, and canopy resistance)

CanT_Actual = actual tree transpiration: f (CanT_Total, root occupancy, available soil moisture)

Calibration of FORECAST Climate for the MKFR Study Area

The following section describes the calibration data that have been assembled to drive the FORECAST Climate model for the MKRF project area. Table 8.1 provides a summary of the data used to calibrate the ForWaDy submodel of FORECAST Climate for the different tree species represented within the model. The calibration data used in its application within FORECAST Climate are listed in Tables 8.1 and 8.2.

Table 8.1 Species-specific parameter values used in the ForWaDy submodel that are specific to simulating evapotranspiration.

Species	**Maximum LAI**[1]			**Canopy**		**Permanent Wilting Point** (%)[4]				**Max. Root Depth**
							Mineral Soil			
	SM[2]	M	H	Albedo	Resist[3]	Humus	SM	M	SH	(cm)
Trees[5]										
Hw	4.5	5.5	6	0.12	0.14	0.11	0.08	0.14	0.20	75
Cw	4	5	5.5	0.12	0.18	0.1	0.07	0.12	0.18	100
Fd	3.5	4.5	5	0.12	0.25	0.08	0.06	0.11	0.17	>100
Dr	3	4	4.5	0.12	0.11	0.11	0.08	0.13	0.19	75
Understory vegetation[6]										
Rubus	NA			0.12	0.11	0.11	0.08	0.13	0.19	60
Vacc.	NA			0.12	0.13	0.11	0.08	0.13	0.19	60
Salal	NA			0.12	0.22	0.09	0.06	0.11	0.17	85

[1] Sets the upper limit for LAI by species. LAI is determined as a function of simulated foliage biomass. Not required for understory vegetation.

[2] Edaphic Class: SM=Submesic site; M = Mesic site; SH = Subhygric site

[3] “Canopy resistance” represents a general measure of the resistance to water loss from foliage via stomata and cuticle.

[4] Refers to the volumetric moisture content at which the species can no longer extract moisture from the soil. Dependent upon the soil texture class.

[6] Trees include: Hw- Western Hemlock (*Tsuga heterophylla*); Cw- Western redcedar (*Thuja plicata*); Fd- Douglas-fir (Pseudotsuga menziesIi); Dr-Red Alder (*Alnus rubra*)

[6] Understory vegetation include: Rubus – Salmon berry shrub (*Rubus spectabilis*); Vacc. – generally blueberry-type shrub (*Vaccinium spp.);* Salal shrub – (*Gaultheria shallon*)

Table 8.2 Parameter values used in ForWaDy that are specific to simulating soil water availability by edaphic class.

Edaphic class	**Soil Texture class**	**Coarse Fragment %**	**Mineral soil depth (cm)**
Submesic	Loamy sand	35	65
Mesic	Silt loam	25	85
subhygric	Sandy clay loam	15	110

Linking Tree Growth with Forest Hydrology

The linkage between the FORECAST and ForWaDy models underpins the operation of FORECAST Climate. This linkage is based upon the iterative sharing of information between models through the creation of feedback loops (see Figure 8.3). One challenge is the fact that the ForWaDy model operates on a daily time step (since this is the relevant interval for many hydrological processes), whereas FORECAST calculates productivity on a yearly time step. The latter model thus provides annual estimates of the key variables used by ForWaDy. These are listed in Table 8.3. ForWaDy output in turn is provided to FORECAST as a series of annual summaries of soil and forest floor moisture conditions, and cumulative measures of water stress for trees and plants.

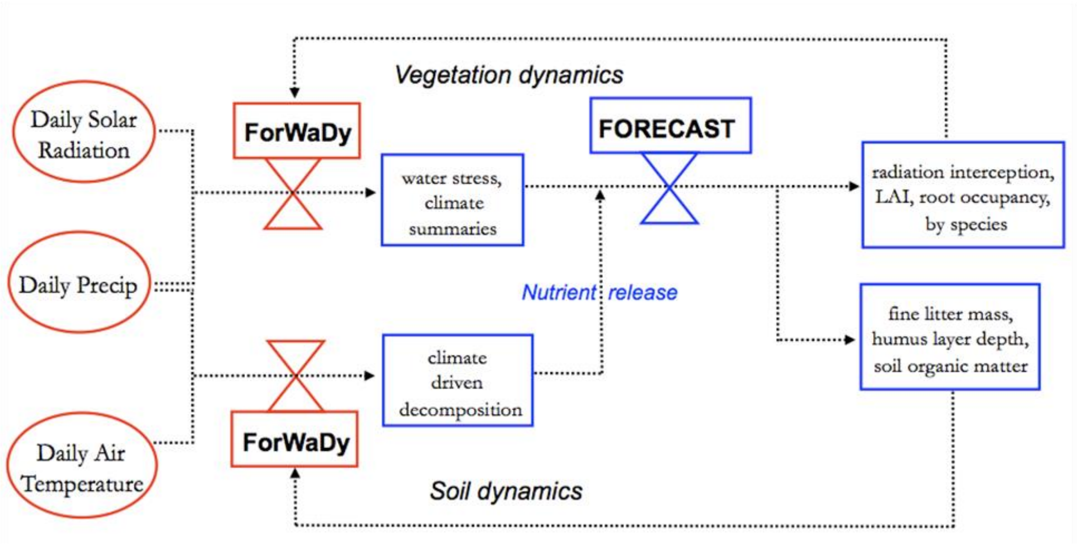

Figure 8.2 A schematic diagram illustrating the feedback loops established to facilitate the linkage of FORECAST and ForWaDy.

Table 8.3 A list of vegetation and soil condition variables passed from the forest growth model (FORECAST) to the hydrological model (ForWaDy). The function of each variable in ForWaDy is also described.

FORECAST	**ForWaDy**	
Variable	**Receiving variable**	**Function**
Canopy light interception	Canopy radiation interception	Drives species specific transpiration
Foliage biomass	LAI[1]	Canopy interception
Fine root biomass	Lateral root occupancy	Soil water uptake capacity within a specific soil layer
Tree age	Rooting depth	Soil water uptake capacity from vertical soil layers
Fine litter mass[2]	Litter mass	Litter layer moisture content
Humus mass	Humus depth[3]	Humus layer water holding capacity

[1] Leaf area index is estimated using a species-specific conversion factor.

[2] Fine litter mass includes foliage, bark, and fruit (cone) litter types.

[3] Humus depth is estimated from humus mass, based on a parameter that defines the proportion of new humus transferred to non-surface layers and an estimate of surface humus bulk-density.

Accounting for Climate Impacts on Tree and Plant Productivity

The impact of climate on tree growth and ecosystem development in FORECAST Climate is focused, in part, on their relationship to temperature and water stress. These relationships are represented using curvilinear response functions, simulated on a daily time step and summarized annually. The temperature response functions (see Figure 8.3) encapsulate the multiple and complex physiological growth processes governing the response of trees and understory growth to mean daily temperature. The relative effect of temperature as a limiting factor on tree growth is captured annually through the sum of daily values. The positive effect of a lengthening growing season can also be represented with this approach. Note, however, that increases in summer temperatures may not necessarily have a positive impact on annual growth rates (Wilmking et al. 2004; see Figure 8.3).

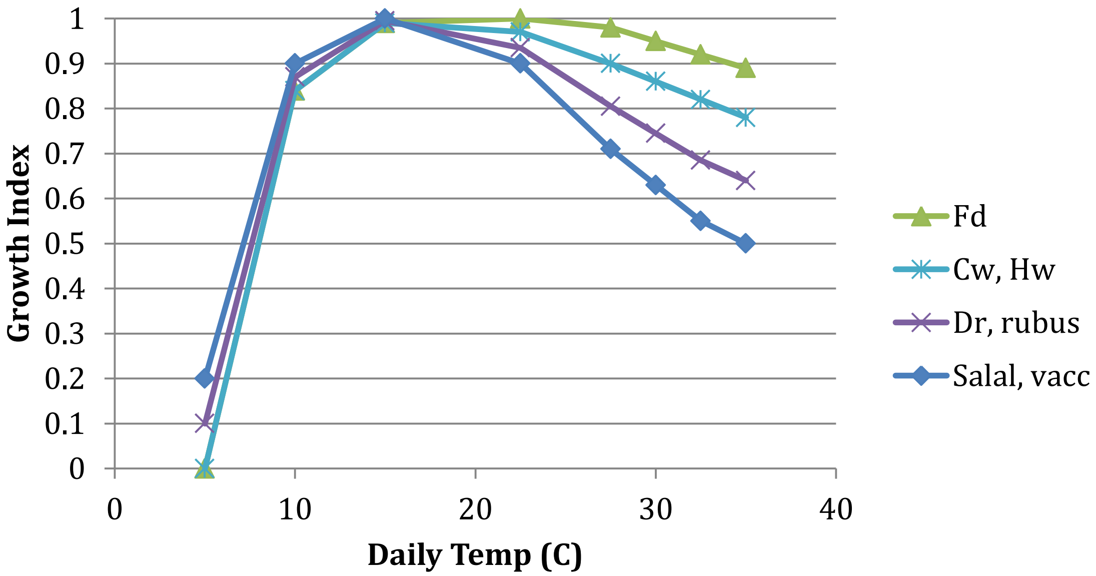

Figure 8.3 Temperature response functions used for trees and understory vegetation.

The effect of moisture availability on plant growth rates in FORECAST Climate is simulated by ForWaDy and calculated as the Transpiration Deficit Index (TDI, see ForWaDy description above). The daily TDI value represents the degree to which a tree species was able to meet its energy-driven transpiration demands; a higher TDI value indicates more moisture stress. As the TDI increases, plants close their stomata to conserve water and there is an associated reduction in photosynthetic production (see McDowell et al. 2008). An evaluation of alternative TDI growth response curves based on tree ring chronologies (see Seely and Welham 2010) indicated that a negative exponential curve best reflected the effect of TDI on daily and annual productivity (Figure 8.4).

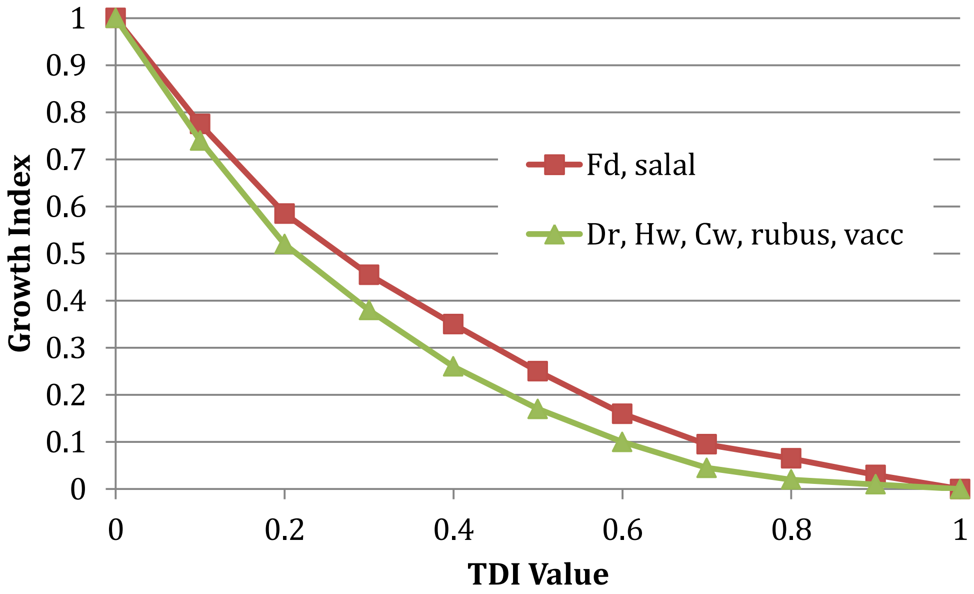

Figure 8.4 TDI response functions used for different tree and understory vegetation species

The temperature and moisture response functions are incorporated into FORECAST Climate through their inclusion in a climate response index function (CRIgrowth). The CRIgrowth function is first calculated daily as the product of the temperature multiplier (Figure 8.3) and the TDI multiplier (Figure 8.4), and then summed over the year to create an annual index. Two types of CRIgrowth values were calculated. First, a climate-normal growth value (normal CRIgrowth) was determined using a 30-year (1975 to 2004) historical climate data set from the weather station associated with each ecogroup. The process of determining a 'normal' value for CRIgrowth involves calculating a CRIgrowth value for each year of the historical climate data set and then calculating an average value for the climate response index (normal_CRIgrowth) over the 30-year period. The second type of CRIgrowth (current_CRIgrowth(i)) is calculated during an actual simulation, for each year, i. A weighted adjustment value is then derived using the normal_CRIgrowth value as the comparative standard (see equation below). The potential growth rate (based on light and nutrient availability) in a given year is multiplied by the weighted climate response index to yield the actual annual growth rate in year, i:

Annual growth rate(i) = potential growth rate(i) *

(current_CRIgrowth(i) – normal_CRIgrowth) / normal_CRIgrowth

where:

potential growth rate(i) = expected growth based on light availability and site quality

current_CRIgrowth(i) = the climate response index for a given year, i normal_CRIgrowth= average climate response index based upon long-term historical climate data

Representation of Drought Mortality

In addition to the changes in growth, climate variability can also induce mortality events (e.g. Daniels et al. 2011). A drought mortality function was developed and implemented within FORECAST Climate to represent these effects. The function, illustrated in Figure 8.5, simulates drought mortality using a response curve in which a two-year running average of species specific TDI is used as a predictor of annual mortality rates. The use of the 2-year running average TDI allows for a decrease in drought mortality when a dry year is preceded or followed by a wet year, but will cause greater mortality in consecutive dry years. An exponential sigmoidal function curve was selected as a good approximation of the significant increase in expected mortality associated with consecutive years with high levels of water stress. The shape of the curve takes into account evidence of enhanced vulnerability of stands to biotic disturbance agents (e.g. bark beetles) during extended periods of extreme moisture stress. The amplitude of the function curve was fit for each species using the historical climate data simulations for reference (to assure that historical climate data led to mortality rates that are consistent with past observations). Two different mortality curves (low and high) were simulated for each tree species to illustrate the sensitivity of the model to varying assumptions with respect to tree susceptibility to drought stress (Figure 8.5).

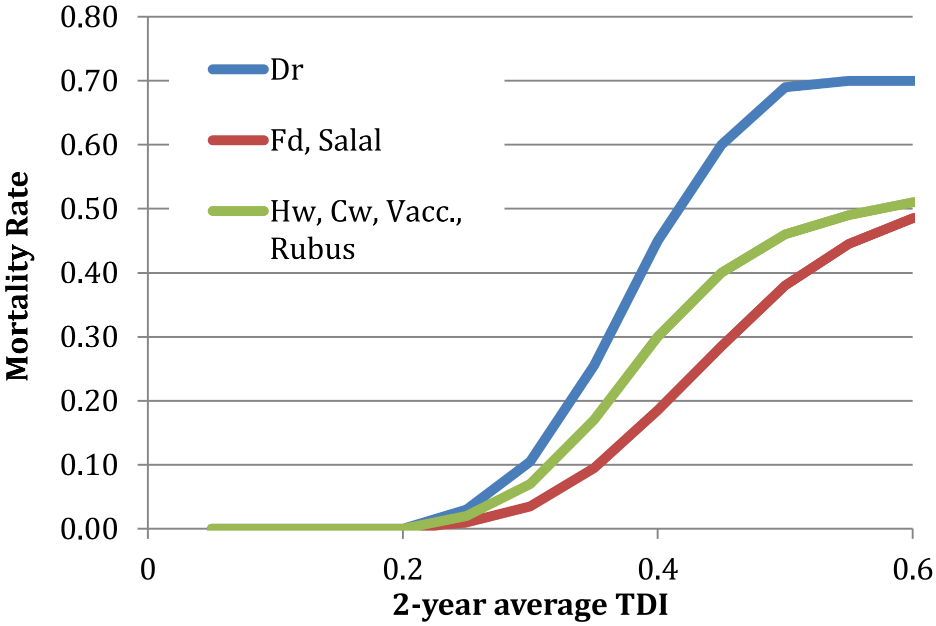

Figure 8.5 Drought-related mortality function showing the realtionship between mortality and running 2-year average of the transpiration deficit index (TDI).

Accounting for Climate Impacts on Decomposition Rates

The decomposition of dead organic matter (litter and soil organic matter) in FORECAST is represented by grouping litter created through the death of specific biomass components into different litter types, each with defined mass loss rates (see Kimmins et al. 1999). In FORECAST Climate, these litter decomposition rates and their associated nutrient mineralization rates are adjusted based on soil moisture content and temperature. A base mass loss rate is provided for each litter and humus type (parameterized from field or literature values) that reflects both the quality of the litter and a 'normal' climate regime. These mass loss rates are then modified within the model to account for the effect of climate, as follows.

Temperature

A variety of techniques have been developed to quantify the effect of temperature on decomposition. The most common are simple calculations of weight loss using litterbags, field soil respiration measures (either by eddy covariance or gas chambers), and laboratory or ^{14}C studies. Consumption of dead organic matter by heterotrophic microbes and fungi is generally faster in warmer environments (Chen et al. 2000, Gholz et al. 2000, and references therein).

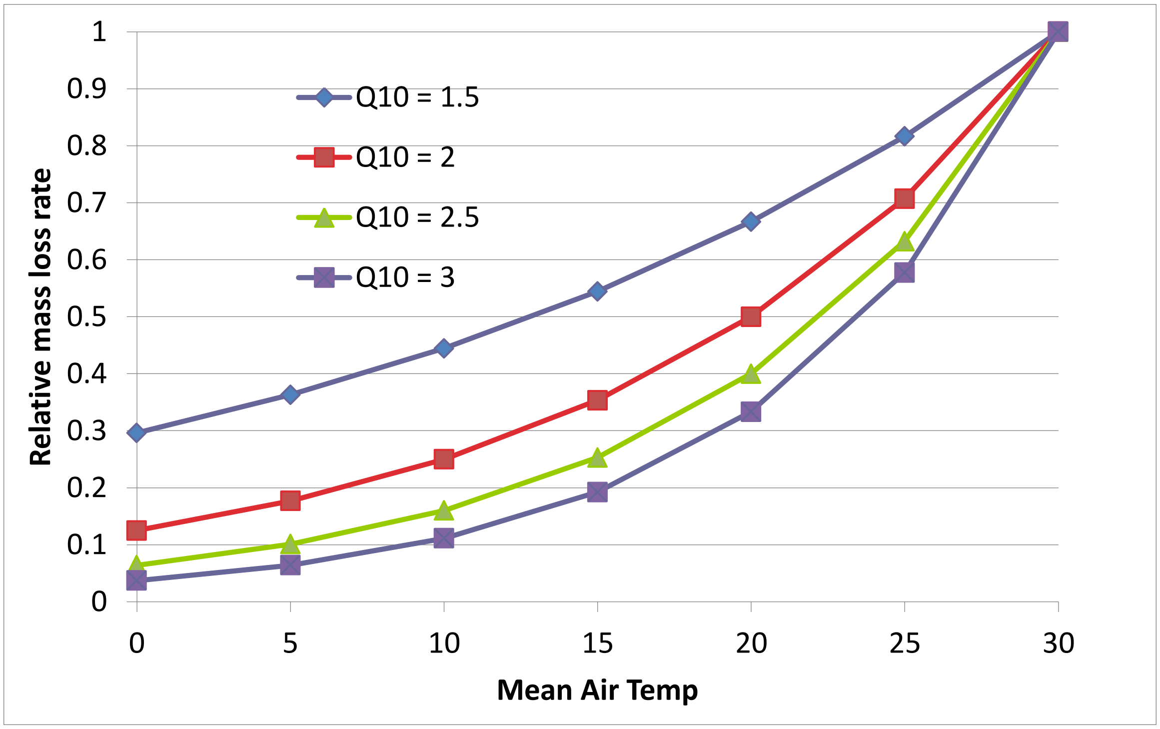

Figure 8.6 Illustration of the effect of a range of Q10 values on the calculation of a relative mass loss rate as a function of mean daily air temperature using the Q10 equation.

Many studies use the Q10 equation to describe effect of temperature on organic matter decomposition rates:

Q10 = (R2/R1) ^ (10/(T2-T1))

where:

R1 = mass loss rate at temperature 1 (T1 °C)

R2 = mass loss rate at temperature 2 (T2 °C)

In FORECAST Climate, the impact of temperature on the decomposition rates of litter and humus is simulated based on the Q10 equation. A default value of 2 was selected for Q10 based on published studies in similar forest types (Chen et al. 2000, Gholz et al. 2000, and references therein). The effect of this value on relative mass loss rates is illustrated in Figure 8.6.

Precipitation and Litter Moisture Content

Precipitation as a factor in decomposition rates has received much less attention than temperature despite the fact its importance has been clearly demonstrated (e.g., Chen et al. 2000, Ise and Moorcroft 2006, Prescott et al. 2004). A key feature of these studies is that decomposition rates are directly correlated to precipitation until a threshold is reached, after which there is little or no additional effect.

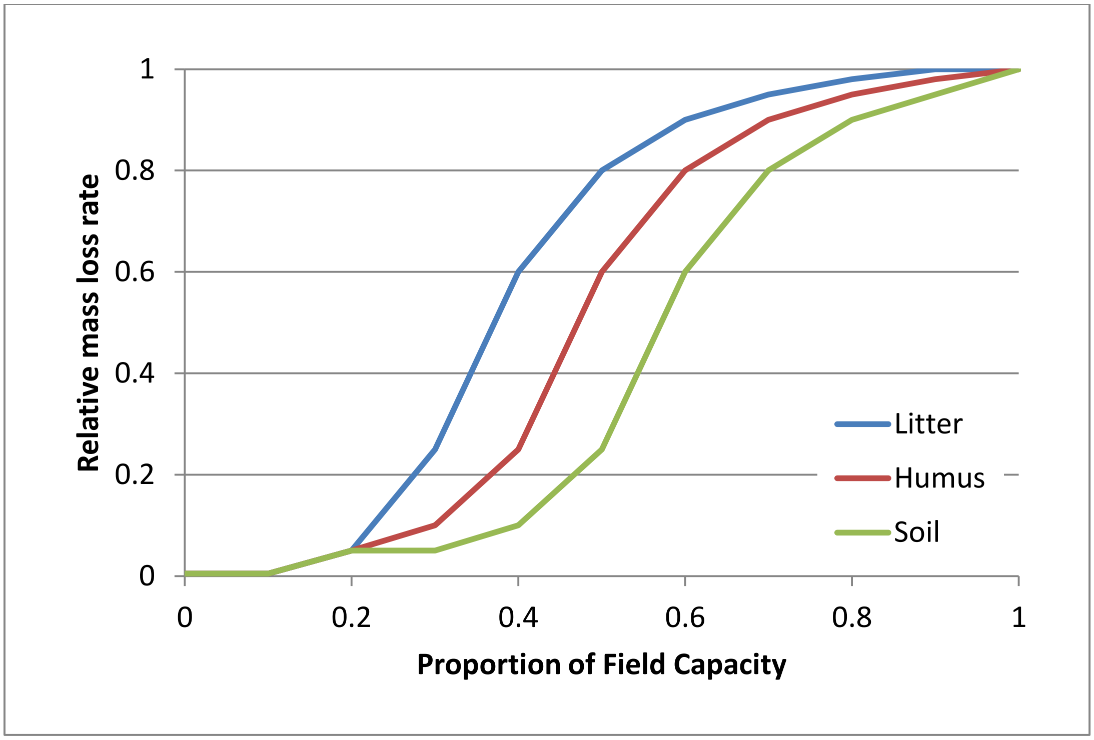

Figure 8.7 Response curves of the effect of daily moisture content (as a proportion of the Field Capacity value) on the relative mass loss rate of litter and humus.

A daily relative mass loss rate is calculated within FORECAST Climate for each litter and humus type using a curvilinear function based upon simulated moisture content in the litter and humus layers (Figure 8.7). Litter moisture content is used to drive mass loss rates for forest floor litter types while humus moisture content is used for any below-ground litter and humus.

FORECAST Climate employs a similar method for scaling decomposition rates to climate as was used for scaling annual growth rates (see above). The temperature-limited relative mass loss rate (Figure 8.6) is multiplied by the daily moisture-limited rate (Figure 8.7 for each litter and humus type, j, to produce a daily decomposition climate response index, CRIdecomp, that is then summed over the year to provide an annual index. A normal_CRIdecomp value is calculated for each litter and humus type based on historical climate data using the same approach described for adjusting tree growth above. A second type of CRIdecomp (current_CRIdecomp(i)) is calculated during an actual simulation, for each year, i. A weighted adjustment value is then derived using the normal_CRIgrowth value as the comparative standard (see equation below).

The base mass loss rate of a given litter or humus type, j, is multiplied by the weighted climate response index to yield the actual mass loss rate in year, i (Annual mass loss rate(i,j)):

Annual mass loss rate(i,j) = base_ rate(j) *

(current_CRIdecomp(i,j) – normal_CRIdecomp(j)) / normal_CRIdecomp(j)

where:

base_rate(j) = expected mass loss rate for each litter and humus type, j

current_CRIdecomp(i,j) = climate response index for each litter and humus type, j, for the current year, i

normal_CRIdecomp(j) = average response index for each litter and humus type, j, based upon long-term historical climate data

Development of FORECAST Climate Analysis Units for MKRF

A series of representative forest analysis units were created and assigned to facilitate the simulation of the 26,467 ha MKRF study area using FORECAST Climate (Table 8.4).

Table 8.4 A description of the analysis units created for the simulation of climate change impacts on the Pitt River pilot study area using FORECAST Climate.

FC_AU	Type	Description	SI range	Age	Avg. SI	Area (ha)
101	Natural	Alder Poor-Medium		All	20.5	842.8
102	Natural	Alder Good		All	27.7	766.9
103	Natural	At/Ep		All	28.8	345.8
104	Natural	Hw-Ba-Pl Poor	<16	>40	9.7	2565.5
105	Natural	Hw-Ba-Pl Med	16-24	>40	19.4	3483.2
106	Natural	Hw-Ba-Pl Good	>24	>40	29.3	4633.2
107	Natural	Cw-Yc-Xc Poor	<16	>40	11.1	501.6
108	Natural	Cw-Yc-X Med	16-24	>40	19.3	1529.9
109	Natural	Cw-Yc Good	>24	>40	29.4	1077.8
110	Natural	Fd-Med	<25	>40	20.2	976.9
111	Natural	Fd-Good	>24	>40	29.5	1,105.9
204	Managed	Hw-Ba-Pl Poor	<16	<41	13.1	66.7
205	Managed	Hw-Ba-Pl Med	16-24	<41	21.2	595.2
206	Managed	Hw-Ba-Pl Good	>24	<41	30.2	1,122.8
207	Managed	Cw-Yc-Xc Poor	<16	<41		0.0
208	Managed	Cw-Yc-X Med	16-24	<41	20.4	138.2
209	Managed	Cw-Yc Good	>24	<41	32.5	32.8
210	Managed	Fd-Med	<25	<41	21.1	181.7
211	Managed	Fd-Good	>24	<41	28.7	306.6
					Subtotal	20,273.5
299	non-productive	maple+willow				421.8
999	Non-forested	Non-forested				5,771.6
					Total	**26,466.9**

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Chapter 9. Modelling Species Regeneration

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Introduction

Species response to climate variability and change varies across spatial and temporal scales (Holtmeier &Broll, 2005). At the macro-scale, climate is the principal driver of species distributions (Huntley et al. 1995); however, autogenic, allogenic, and biogenic processes interact with species ecophysiology and resource availability to affect species distributions at finer scales (Pearson et al. 2004; Guisan and Thuiller, 2005). At finer-scales, species presence or absence is typically governed by changes in resource availability as a result of the changes in the edaphic environment (Florence, 1964) and by species phenology (Chuine and Beaubien, 2001). Species are most sensitive to changes in the environment however within their regeneration niche since it is the most critical phase for their survival (Bell, 1999). Grubb (1977) and Young et al. (2005) defined the regeneration niche as the set of environmental parameters that determines the probability that replacement of mature individuals will occur and as the set of environmental parameters that allows seeds to germinate and become established. Typically, regeneration in ecological models are modelled stochastically (Burton & Cumming, 1995) but are not based on the mechanisms governing regeneration such as the key process of germination and its phenological interaction with temperature, frost and drought (Shugart & Noble, 1981, Mok et al. 2012). Instead regeneration is based on growing degree days (GDD), soil moisture levels and light availability (Bugmann, 2001). Climate however can change the ecological cues seeds and seedlings depend on for regeneration, causing shifts in timing and success (Walck et al., 2011). The inclusion of processes affecting germination and establishment are therefore needed for understanding the potential impact of climate variability and change on species distribution (Mok et al., 2012).

To address the role of regeneration in modelling species response to climate variability and change we utilise the TACA-GEM model (Nitschke and Innes, 2008; Nitschke et al. 2012; Mok et al. 2012). TACA-GEM is a mechanistic species distribution model that focuses on modelling the response of tree species to changes in climate and soil moisture within their regeneration niche. The model has two variants TACA-EM and TACA-GEM, the former models establishment as a function of habitat and phenological suitability while the latter incorporates processes that govern seed ecology (dormancy and germination). For brevity we will refer to both models as TACA.

Model Components

The TACA model includes four main components: habitat; phenology, germination, and extreme events (Figures 9.1-9.4). Species bioclimatic profiles that determine species response to temperature, frost and moisture as seedlings represent the species habitat niche; which Grubb (1977) defines as the environmental conditions that allow plants to develop and grow once established (Figure 9.1). The phenology component models the seasonal development of plants in interaction with temperature, dormancy and frost occurrence (Figure 9.2). The germination niche models the ability of seeds to germinant and germinant to survive (Figure 9.3). The extreme event model affects species regeneration by killing off seedlings that regenerate in favourable years but are subjected to prolonged/ extreme drought events or extreme frosts that would result in mortality (Figure 9.4). The inclusion of extreme events can improve the predictions of species response to climate (Zimmerman et al. 2009). Climate inputs to TACA are minimum temperature, maximum temperature, solar radiation and precipitation on a daily time step. Currently there are two climate input options; 10 years that are structured to represent the climate variability for a site and 50 years of continuous climate data for a site.

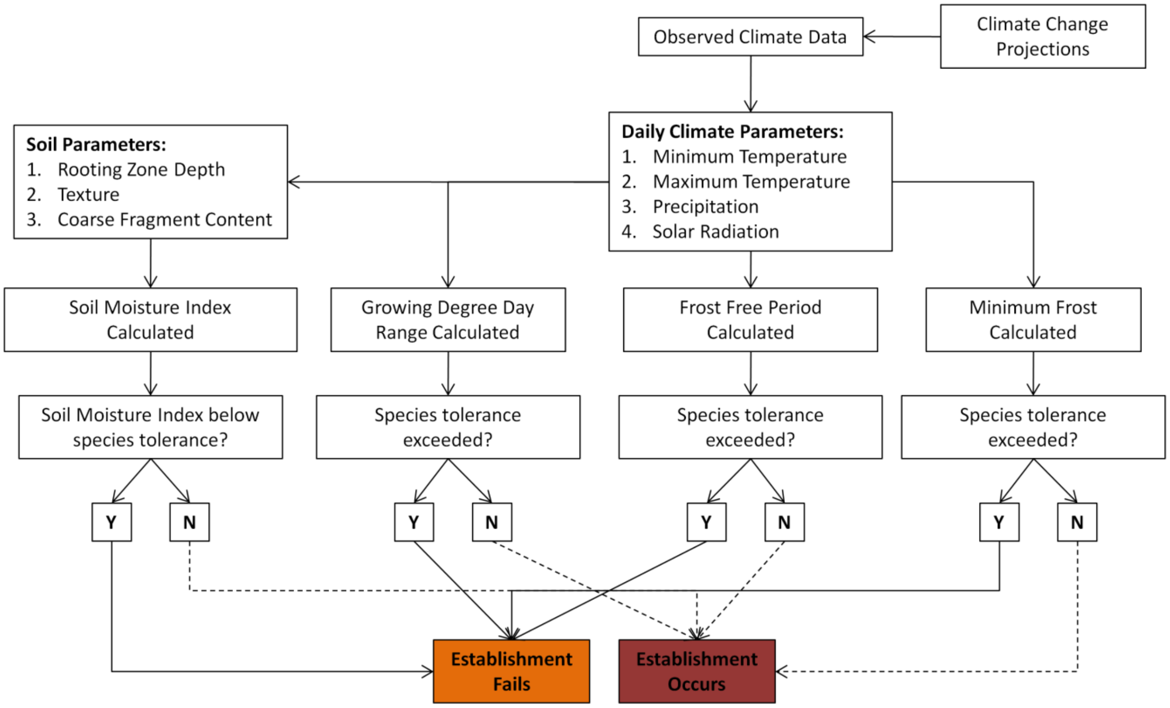

Figure 9.1 Conceptual framework for Habitat niche elements and climate and soil inputs used in TACA.

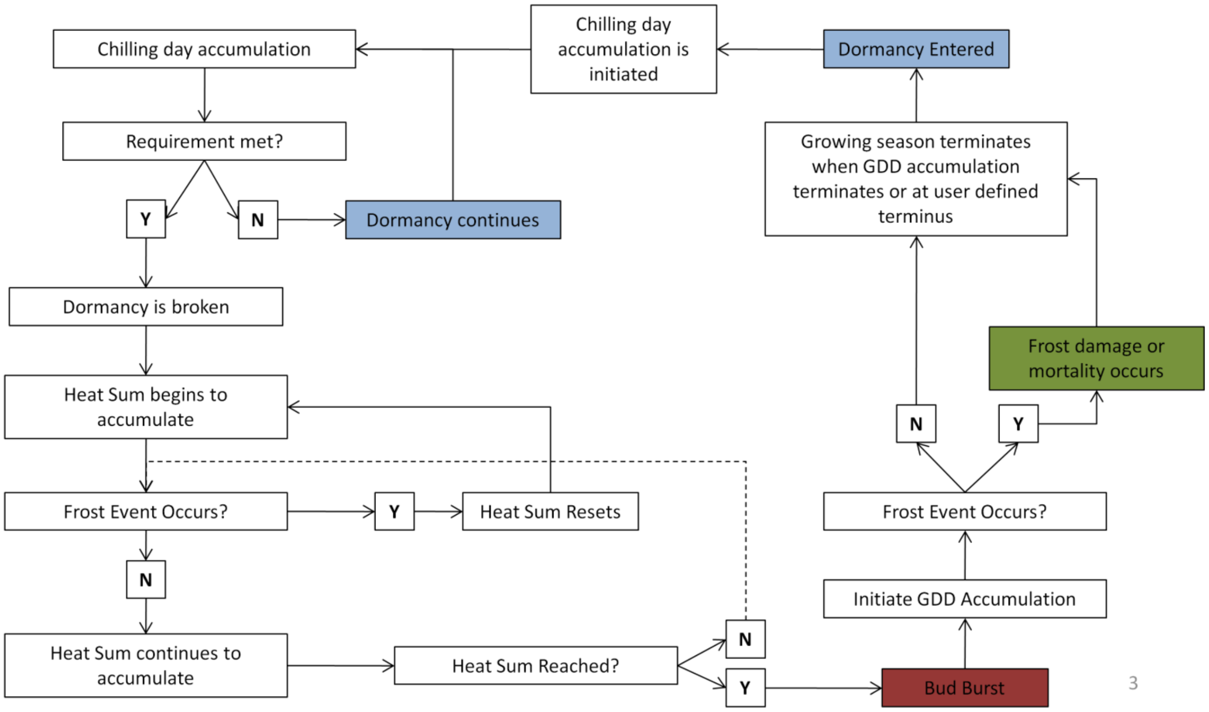

Figure 9.2 Conceptual framework for phenology niche elements in TACA.

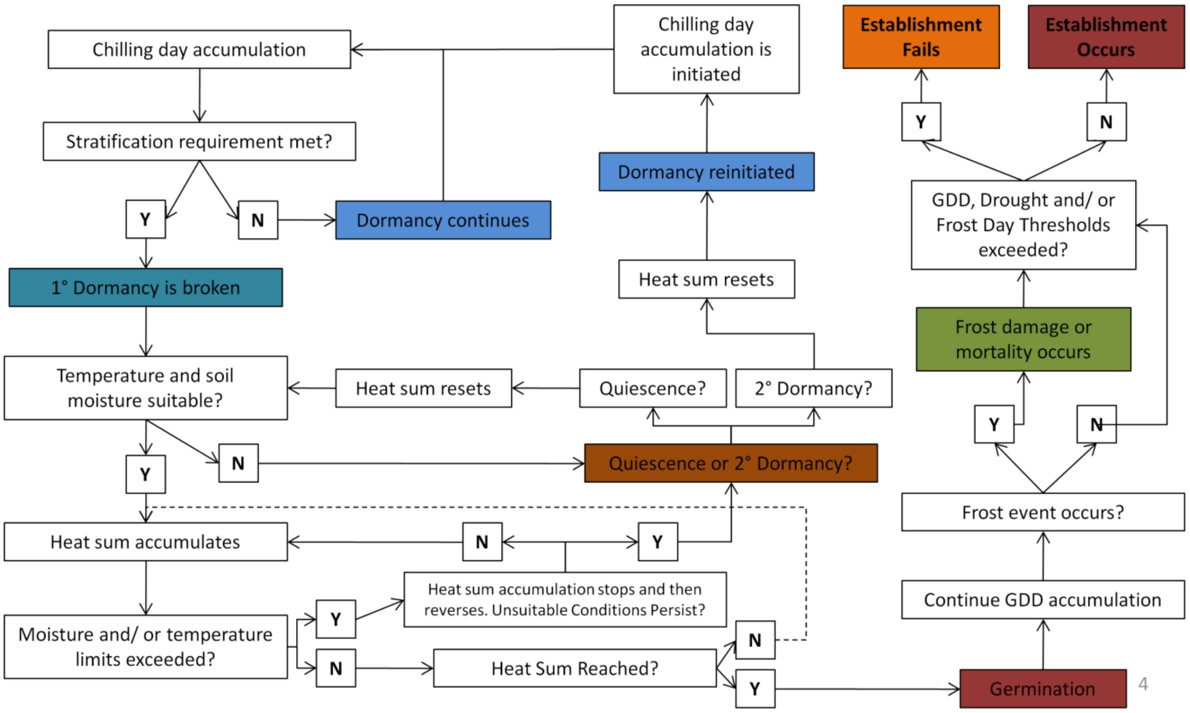

Figure 9.3 Conceptual framework for germination niche elements used in TACA (adapted from Mok et al. 2012).

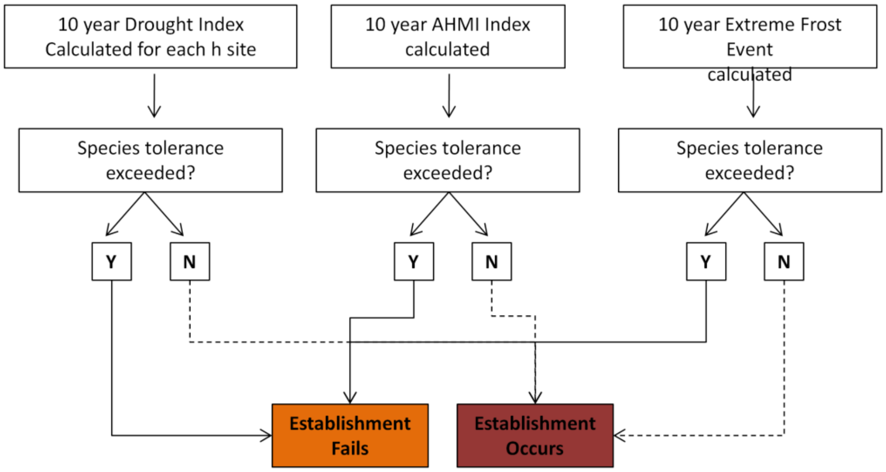

Figure 9.4 Conceptual framework for extreme event module used in TACA.

Major Elements in TACA

Growing Degree Day (GDD)

In TACA, growing degree day (GDD) thresholds are used to determine the lower and upper relationship limits between temperature and growth. If the maximum and minimum requirements are not met, minimum growth rates occur that can result in species mortality. If the minimum threshold is not met or the maximum threshold is exceeded, it is assumed that the regeneration niche of a species is exceeded. The regeneration niches of species are narrower than mature trees so this assumption may not limit the presence/absence of mature trees but may prevent seedling establishment. In TACA, GDD are calculated by summing the number of degree days above a species-specific baseline temperature for an entire year. Loehle and Leblanc (1996) recommend increasing any calculated GDD range by a factor of 1.25 in order to expand the GDD range to correct for non-climatic factors that may contribute to the ecological or expressed niche of a species. We apply this recommendation in TACA. The use of GDD to limit species establishment the common approach used in many models. TACA uses the growth and response functions utilised in the BRIND (Shugart and Noble 1981) and ZELIG++ (Burton and Cumming 1995) models to estimate species suitability to temperature (see Figure 9.5).

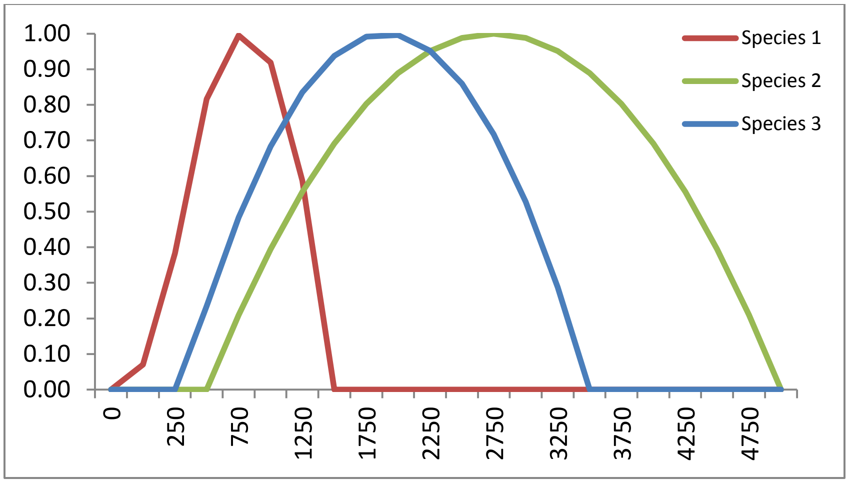

Figure 9.5 Example of species response functions to GDD used in TACA. Figure illustrates three theoretical species response curves.

Soil moisture

The effect of seasonal drought and/ or soil moisture limitations is modelled as a response function to the proportion of the year that soil water potentials fall below the turgor loss point of a species. Species establishment fails when the proportion of the year where soil water potentials fall below a critical threshold (Figure 9.6). To model soil water potential TACA uses the van Genuchten soil water retention model (van Genuchten 1980). Soil water potential is modelled as a function of soil texture, available water storage capacity and field capacity. This function is also used to model the effects of soil moisture on seed germination. Species phenology can be a key determinant of species distributions (Chuine and Beaubien, 2001).

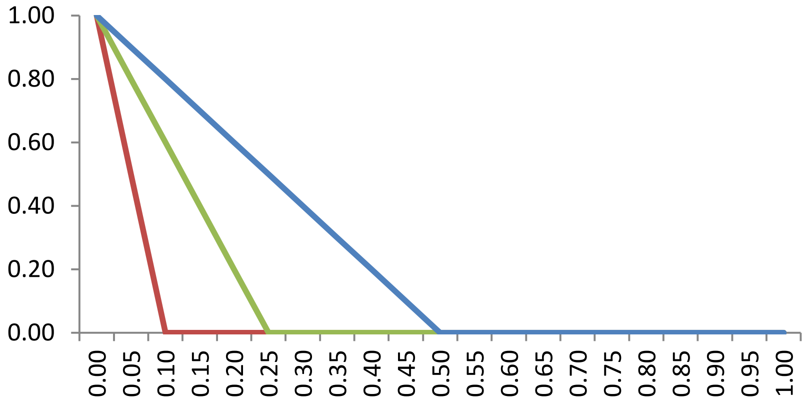

Figure 9.6 Example of species response functions to drought as a function of proportion of year under water deficit. Water deficit is defined by the proportion of the year where soil water potentials fall below the turgor loss point of species.

Frost

Frost in particular can have a significant impact of species establishment (Nitschke and Innes, 2008; Mok et al., 2012). Hamann and Wang (2006) found that the annual number of frost days had a significant interaction with observed species ranges in British Columbia. Species-specific susceptibility to growing season frosts is used to modify the establishment of a species. Frosts interact with bud development to influence the timing of bud flush and also affect a species regeneration success if a frost occurs following bud flush (See Figure 9.7). The length of the frost free season is also used in TACA to control the establishment of species at high latitudes and elevations (Shugart and Noble, 1981).

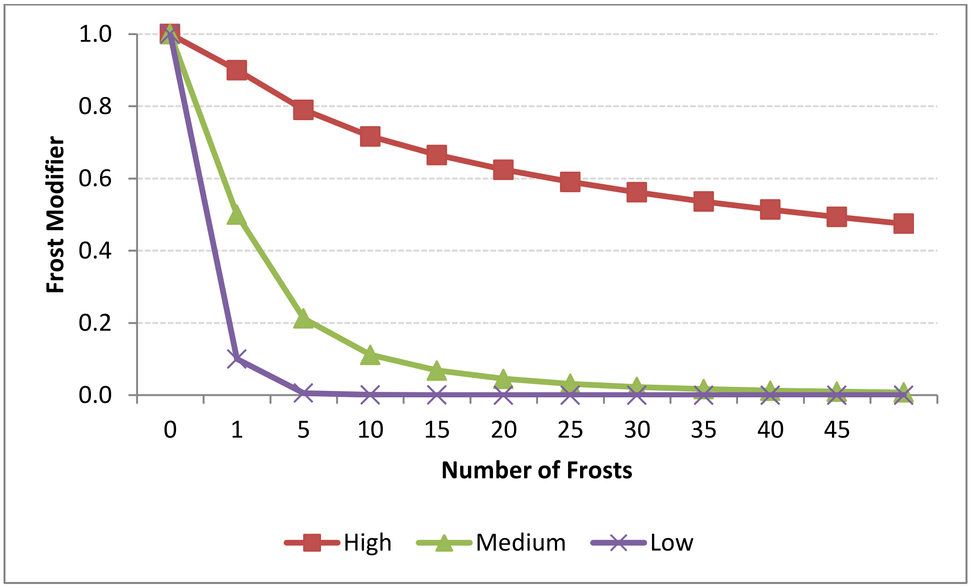

Figure 9.7 Species response functions to the occurrence of growing season frost events. Example illustrates the response of species with high (0.9), medium (0.5) and low frost tolerance (0.1).

Seed Ecology: Germination and Establishment Module

To effectively model regeneration realistically we need to consider the processes that drive plant recruitment. The germination and establishment module (GEM) in TACA has been developed to address these key processes (Mok et al. 2012). The main processes that TACA addresses are stratification, dormancy (physiological and physical) and the timing and proportion of germination as a function of stratification, temperature, and moisture. Following germination, the survivorship of germinants is modelled as a function of the timing of germination in relation to frost occurrence and seasonal moisture deficits. The drought and frost affects are modelled as described above.

To break primary dormancy some species require stratification. In this function the number of days of stratification required to break primary dormancy is specified as is the response function that determines the proportion of germination given the length of stratification. At this time, linear and quadratic functions are accepted. Figure 9.8 illustrates the response functions for five species in southeast Australia. For many species periods of chilling will stimulate germination to occur much faster than when no stratification occurs (Li and Burton, 1994). In TACA, response functions that account for the effect of stratification on the timing of germination are included. Figure 9.9 provides an example of species response functions. To account for the relationship between germination and heat sum accumulation TACA uses probabilistic response functions to model the timing and abundance of germinant within a year. Figure 9.10 illustrates an example of a response function that can be applied in TACA. Linear, quadratic, and cubic functions can be used in the model but flexibility exists to add other response function forms. As germination can be prevented by soil matric potentials or low/ high temperatures the use of functions as illustrated in Figure 9.10 allows for germination to occur between periods of unsuitable temperature/ moisture conditions until 100% of seeds germinate. The model also includes the processes of secondary dormancy and quiescence (period of rest) which are initiated by prolonged moisture deficits or high temperatures which can prevent or delay germination.

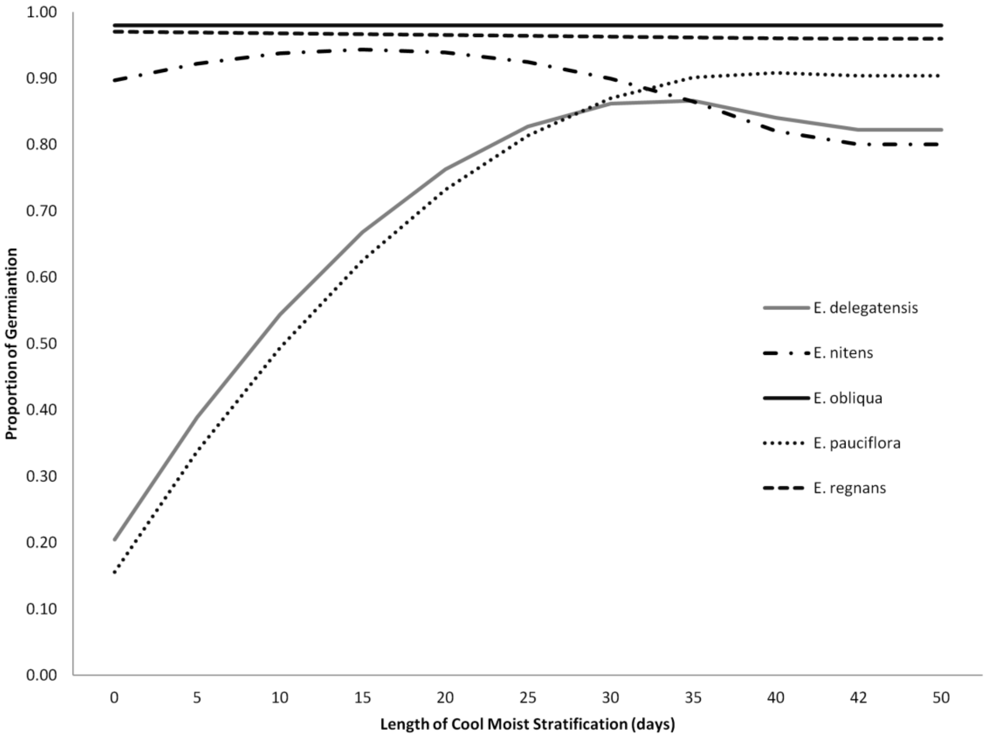

Figure 9.8 Response of species germination abundance as a function of stratification length (adapted from Mok et al. 2012).

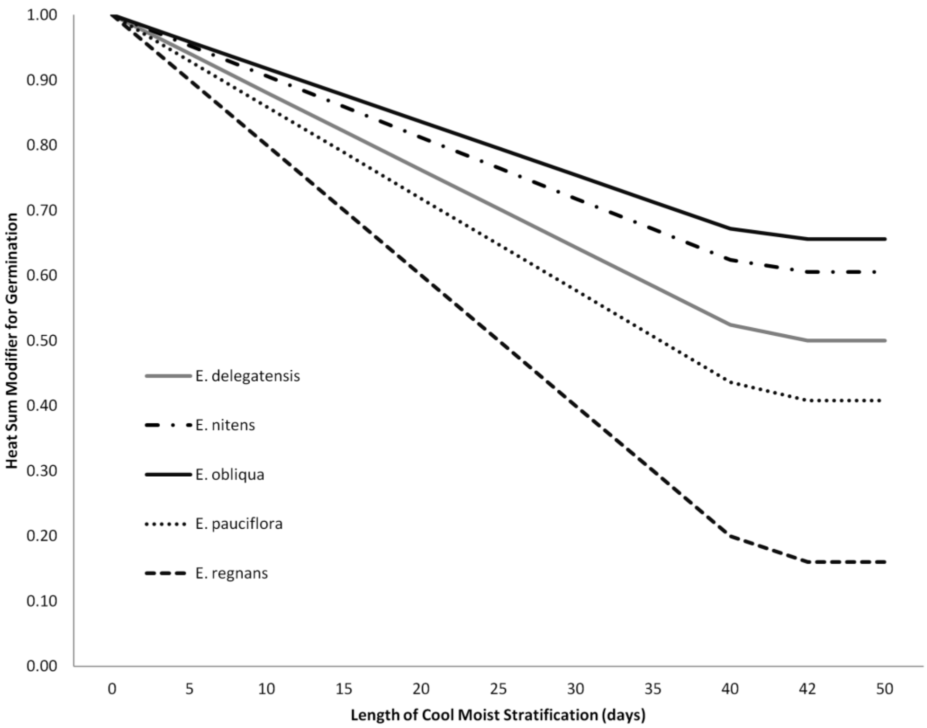

Figure 9.9 Response functions to account for the impacts of stratification length on the timing of germination (adapted from Mok et al. 2012).

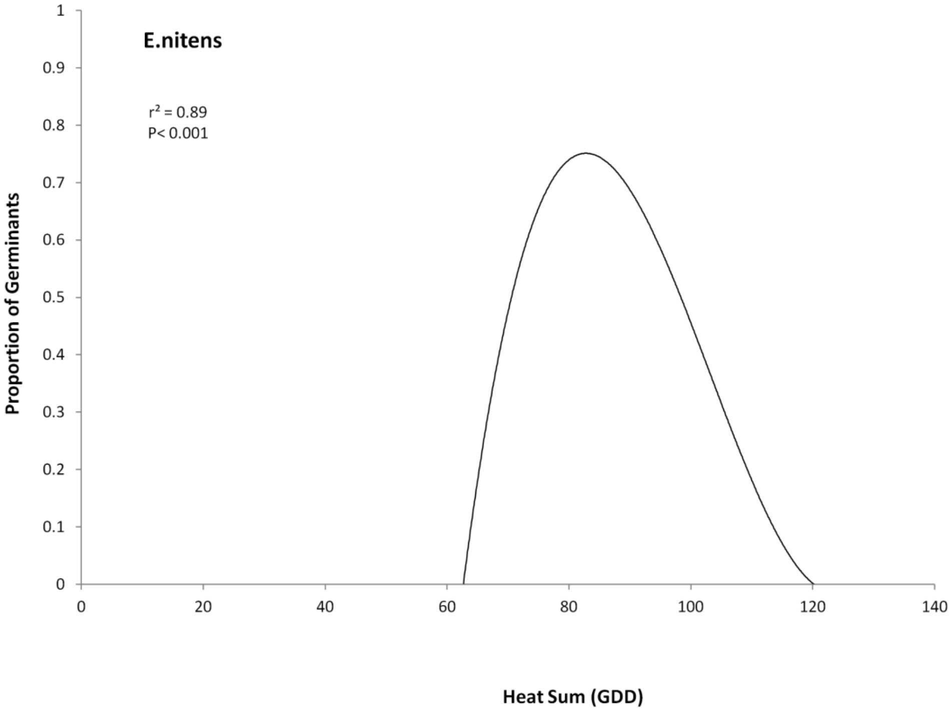

Figure 9.10 Example of a probabilistic germination response function that models the proportion of germination as a function of growing degree days (GDD).

Application of TACA-GEM

Figures 9.11 to 9.13 illustrate three common outputs that can be generate from TACA-GEM. Figure 9.11 demonstrates the application of TACA to a location with daily climate data within a certain ecosystem type that is characteristed by edaphic (topographic) variation in soil/ site types. In this example, a variable response in species establishment is modelled to occur under all climate scenarios and sites until the 2080s when the model predicts the species to be unable to regenerate. The model in this case is run with 10 daily climate scenarios that represent the 10th, 25th, 50th, 75, and 90th percentiles in observed mean annual temperature and precipitation for the given location. Climate change is applied using a direct adjustment approach which modifies temperature and precipitation based on monthly predictions of climate change. Germination is not modelled in this example just establishment following Nitschke et al. (2012).

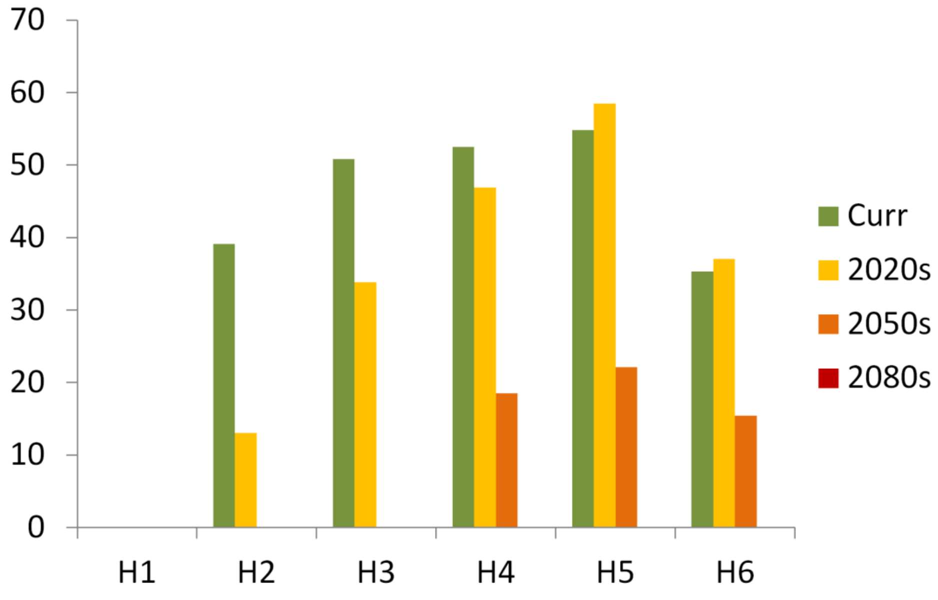

Figure 9.11 Decadal establishment coefficients (y-axis; maximum score is 100%) under varying climate and edaphic conditions (H1-H6: xeric to subhygric). Results show a fluctuation in the establishment coefficient of lodgepole pine (*Pinus contorta* var. *latifolia*) across six site types with the same climate inputs and the affects of climate change in a Montane Spruce ecosystem near Williams Lake, British Columbia, Canada.

Figure 9.12 demonstrates the application of TACA-GEM to a location with daily climate data that is characterised by two site types. The model in this case is run with 50 years of continuous daily climate data. The model tracks the occurrence and abundance of germination across the time series but also which germination events lead to establishment of seedlings and hence successful recruitment events.

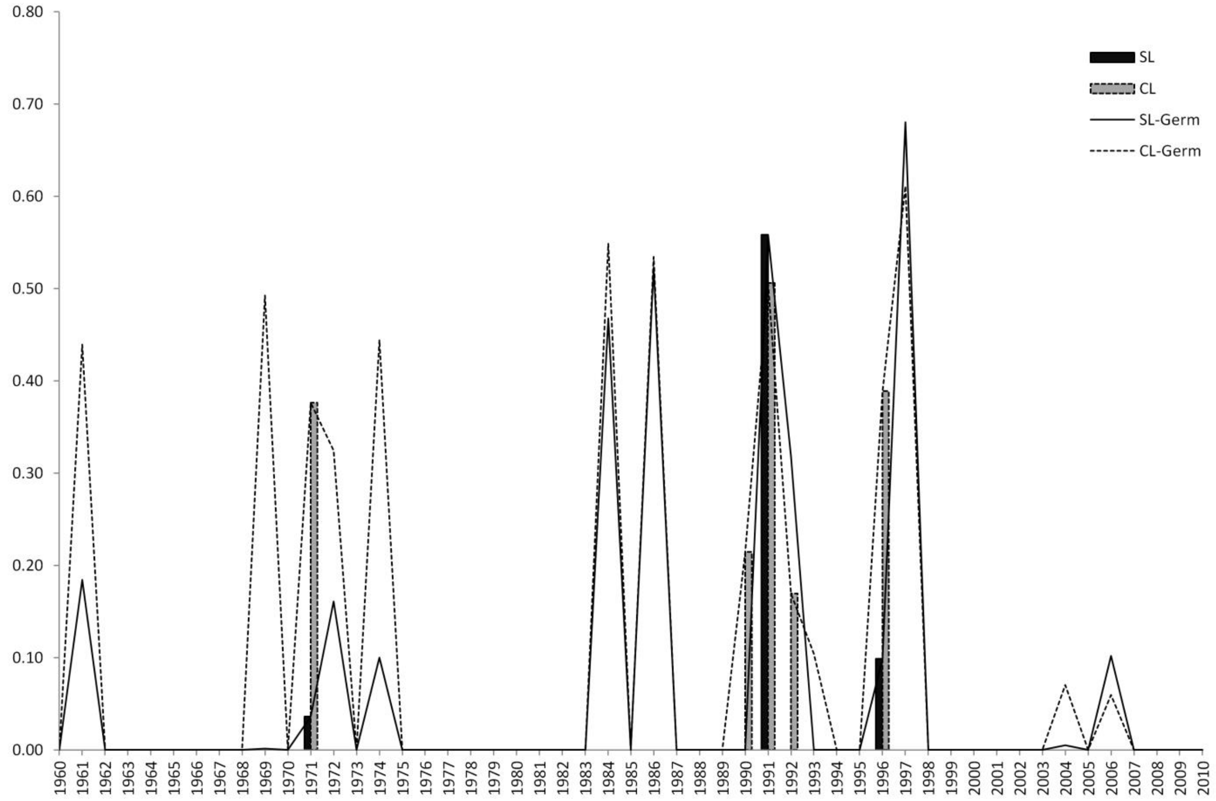

Figure 9.12 Modelled Time series of regeneration. Results show the annual fluctuation in the germination and establishment of Pinyon pine Pinus edulis) over the last 50 years near Los Alamos, New Mexico, USA on two site types (sandy loam (SL) and clay loam (CL)). Lines indicate germination events (proportion of seeds) while bars indicate successful establishment events (proportion of seedlings).

The two previous examples illustrate the use of TACA-GEM in an aspatial context. For the model to be useful for determining landscape responses to climate variability and change the model must be combined with spatial data on climate, topography and soil. Figure 9.13 illustrates the application of TACA-GEM for investigating the impacts of climate change on the regeneration ability of mountain ash (*Eucalyptus regnans*) across the central highlands forest management area in southeast Australia. In this case study, the model is run on 10 daily climate scenarios at a 20 km resolution using five soil types. Species regeneration scores from 600 climate grid points were used to develop statistical models as a function of elevation for each soil type and climate time period (historic to 2080s) then applied to a digital elevation model. The results from this form of analysis are then analysed in GIS and also used to generate inputs of regeneration for use in the landscape model LANDIS-II.

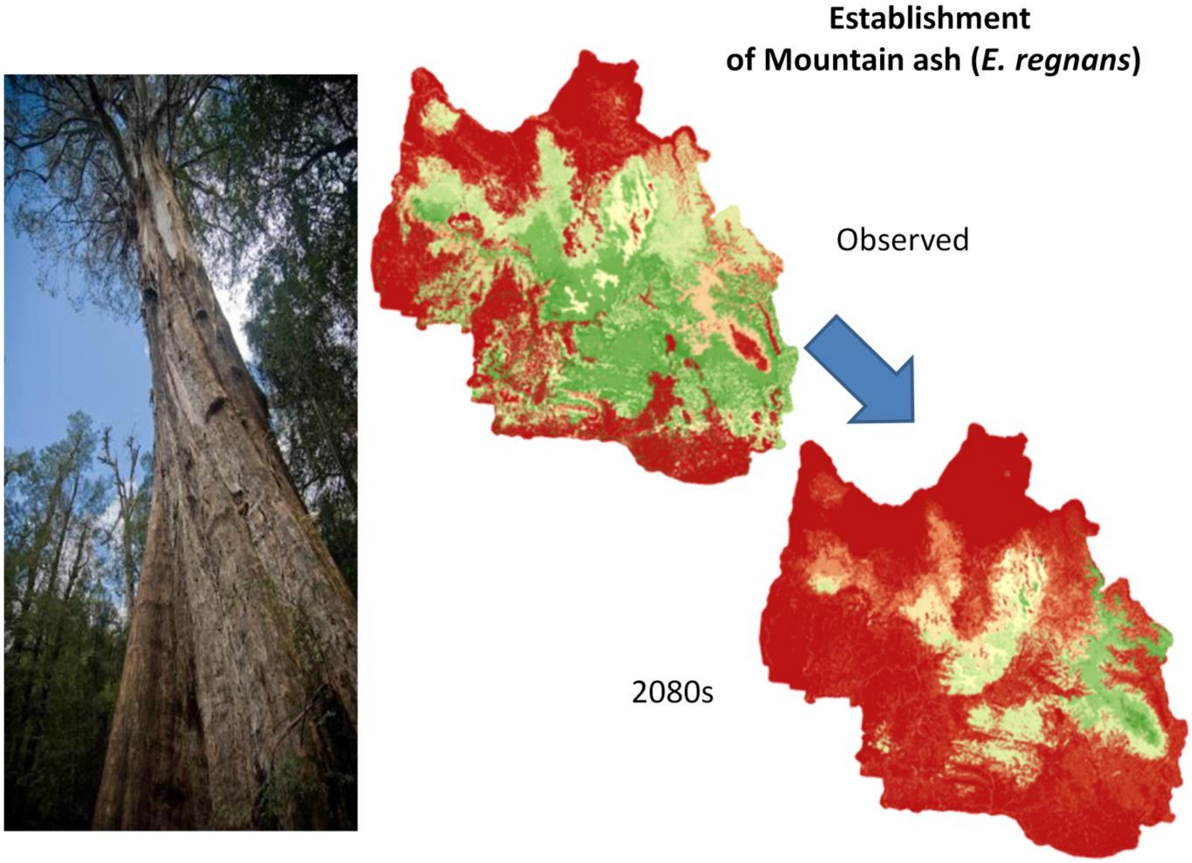

Figure 9.13 Spatial and temporal changes in regeneration for mountain ash (Eucalyptus regnans) modelled using TACA-GEM across a two million hectare landscape in southeast Australia. Models were run on daily climate scenarios at a 20 km resolution and account for changes in soil type.

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