APFNet Project Technical Report on

Adaptation of Asia-Pacific Forests to Climate Change

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Executive summary

Climate change is one of the most important threats to the capacity of forest landscapes to provide ecological, economic and social services in the Asia-Pacific region. Further, it has been established that healthy, well-managed forests can help to mitigate the rate of climate change by acting as sinks for atmospheric carbon. As climate regimes continue to change throughout the region, it is essential that forest managers develop effective management strategies to maintain resilient forest ecosystems and associated communities. However, there is remarkably little evidence that science-based decision-making processes are being incorporated into forest management practices in the region. As a result, considerable uncertainty exists over management policies aimed at enabling forests and forest-dependent communities to adapt to climate change.

In this research project, we first examined the current status of studies in climate change to identify knowledge gaps and develop initial hypotheses. We then applied state-of-the-art technologies and analytical approaches from climate modelling, geospatial analysis, and sustainable forest management to develop essential tools and frameworks to better facilitate climate change adaptation. Using tools developed in this project and pilot field studies carried out by the research network, we evaluated adaptive strategies and developed a series of recommendations for sustainable forest management practices in the Asia-Pacific region. The major outputs of this project include:

1) A scientific and a policy review that reviewed the basic science of climate change and what the Asia Pacific may expect, and accumulated information on various policy measures in the Asia Pacific region that have been implemented to either adapt to, or mitigate, climate change from a forestry perspective;
2) ClimateAP, a high-resolution climate model, which generates scale-free climate data for a large number of climate variables for historical and future periods. It may serve as an essential tool for the entire Asia Pacific to facilitate and promote climate change related studies and applications in this region;
3) Climate niche models built for five major forest tree species in this region including Chinese fir, Chinese pine, Masson pine, Douglas-fir, and Blue gum, and their consensus projections generated for future periods to provide scientific basis for assessing the impact of climate change, identifying the most vulnerable species and populations, and formulating adaptive management strategies;
4) A spectrum of models applied to pilot sites including an evaluation of the long-term impact of climate change on the growth of Chinese fir in Fujian Province using the process-based model (FORECAST Climate), and identification of key indicators of ecosystem services and the development of decision-support tools for evaluating alternative management strategies in the form of a trade-off analysis;
5) A Google Map based web tool to facilitate data access and spatial visualization of climate data and climate niche projections, which will considerably promote information flow and knowledge transfer from scientists to policy makers and stakeholders; and
6) Workshops, conferences, surveys and extension notes, and a network built comprising scientists, stakeholders and policy makers from China, Canada, USA, and Australia to strengthen the project team, and to facilitate information sharing and knowledge transfer.

In addition, we have also generated outcomes from extended research work including fire disturbance parameterizations for China's pilot sites, and LiDAR implication in subtropical forests that has been generating satisfactory results. In total, we have published or submitted 20 papers in scientific peer-reviewed journals.

This project has supported the development of several important tools that will allow forest managers to better access information to aid in the development of effective strategies to address the challenges presented by climate change. These advances will help to support on-going efforts to increase the resilience of natural forests, plantations, and forest-dependent communities, and to facilitate forest rehabilitation in the Asia-Pacific region. A series of recommendations have been developed from the integration of climate and ecological model predictions with observed interactions between forest management practices and climate change at pilot sites, which will provide opportunities to improve forest management practices to facilitate adaptation to climate change. The project has also improved understanding of the impacts of climate change on ecosystems and forests, and enhanced the awareness of the scientific community to potential changes in climate throughout the region.

We thank APFNet wholeheartedly for their support over the past three years and hope to have their continued support for many years to come!

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Introduction

According to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), temperatures are predicted to rise an average up to 4.8°C globally by the end of the century. This magnitude of temperature rise and its associated climatic changes could overwhelm the resilience of even the most adaptable forest ecosystems and threaten their components, including plants and animals. Bioclimate envelopes (suitable climate niches) for the current forest ecosystems and their components, particularly forest trees, are predicted to shift much more rapidly than forest trees can migrate naturally. As a result, some local forest tree species currently occurring in these ecosystems will not be able to adapt to their local environments in the future. This will compromise the productivity and resilience of these ecosystems, and may change the forest landscapes from carbon sinks to carbon sources.

For instance, the 18 million hectares of forests affected in British Columbia by a mountain pine beetle outbreak induced partly by warmer temperature associated with climate change serves as a good example of what could happen elsewhere. According to the IPCC, ecosystems of the Asia-Pacific region are particularly vulnerable to climatic changes such as temperature and aridity that are expected to increase more rapidly in parts of this region than the global average. Climate change is therefore considered to be the most important threat to the capacity of forest landscapes to provide ecological, economic and social services. The development of forest management strategies to better mitigate and adapt to climate change is a pressing challenge facing the scientific community, stakeholders, and policy makers.

The potential for forests to mitigate climate change through carbon sequestration represents a major opportunity for forestry. This is particularly important given the stated policy aim of planting 20 million hectares of forests in this region in the coming years. In establishing new plantations, there is an opportunity to select tree species that match current and future climate conditions in order to avoid maladaptation. Meanwhile, climate change will also bring new opportunities. Some planting sites may become suitable to grow species that grow faster and that are economically more valuable than the current local species.

The appropriate management of existing forests and the planning of the new plantations are critical to the adaptation of forest ecosystems to climate change, and to enhance the role of forests in mitigation of climate change. However, there is remarkably little evidence of sufficient quality to be incorporated into science-based decision-making, and as a result, there is considerable uncertainty over the most appropriate policies to enable forests and forest-dependent communities to adapt to climate change. There is a critical need to acquire relevant scientific knowledge and to develop fully functioning networks of scientists, stakeholders and policy makers. This will ensure the transfer of the scientific knowledge directly to decision-making processes.

In order to adjust forest management practices for existing forests and to take advantage of the opportunity for species selection in new plantations, we must understand the potential impact of climate change on forest ecosystems under different climate change scenarios. An effective approach is to first predict the shifts in bioclimate envelopes of forest ecosystems and forest species ranges under future climates. These predictions will provide the scientific basis for assessing the vulnerability of different ecosystems and developing adaptive strategies. A representative example of research in this field is the niche-based modelling approach developed at the University of British Columbia (Hamann and Wang 2006, Ecology) using multivariate statistics. Our team member, Dr. Tongli Wang, using a machine-learning approach “Random Forest”, has substantially improved the accuracy of the model and advanced this approach. However, in order to develop and apply this model, we need to have reliable high-resolution climate data for current and future periods. Dr. Wang, in collaboration with his colleagues, has developed a high-resolution climate model for Western Canada called "ClimateBC" and lately expanded this to cover western North America (ClimateWNA). The model downscales PRISM climate data (commercially available) developed by Oregon State University from a resolution of 4 x 4 km to point data (scale-free) through a combination of bilinear interpolation and a sophisticated elevation adjustment. The downscaled climate data reflect topography much better than the original PRISM data.

With such high quality climate data and using the Random Forest modelling approach, Dr. Wang was able to model the forest ecosystems of British Columbia (Biogeoclimatic Ecosystem Classification (BEC)) with high accuracy, and was able to predict shifts in bioclimate envelopes for the ecosystems in future periods. As ecosystem classifications can serve as a fundamental basis for forest resource management activities in the province, the predicted future forest ecosystems provide a scientific basis for developing adaptation strategies for many forest management activities, including tree species selection, pest and disease control, fire control, and silvicultural practices. Now that a similar bioclimate model has been developed for the Asia-Pacific region, these modelling methodologies can be used to model and predict forest ecosystems and species distributions for future climates in this region.

Similarly, predictions of shifts in tree species range are a critical component in a climate change adaptation framework. Using the same approach as described above, shifts in suitable climate niches for forest tree species have also been predicted. Such information can provide the scientific basis to match forest tree species to their favourable climate conditions in a changing climate. This research is already playing an important role in climate change adaptation frameworks in Canada, and has become highly influential in western North America’s climate mitigation policy. Through this project, we extended and improved this work to the entire Asia-Pacific region.

In parallel with climate niche models, process-based models also play an important role in evaluating the impact of climate change on forest stand level productivity, water balance, and carbon storage. FORECAST Climate (Seely et al. 2014) was developed as an extension of the hybrid forest growth model FORECAST (Kimmins et al. 1999) created through the dynamic linkage of FORECAST with the stand-level hydrology model ForWaDy (Seely et al. 1997). The linked model is capable of representing the impacts of climate change on forest growth dynamics. TACA is a mechanistic species distribution model (Nitshke and Innes 2008) that facilitates an analysis of the response of trees to climate-driven phenological and biophysical variables. It assesses the probability of a species being able to regenerate, grow, and survive under a range of climatic and edaphic conditions. FORECAST Climate and TACA models were employed in pilot sites in temperate and sub-tropical regions to evaluate the long-term impacts of alternative climate change scenarios on forest growth and development. Results from the models were subsequently utilized in analyses of value tradeoffs associated with alternative forest management practices.

The objectives of this project were to develop some essential tools and modelling frameworks to enhance the capacity of the forest communities to adapt to climate change. The high-resolution climate model developed in this project will serve as an essential tool to generate historical and future climate data for any location in the region, which will facilitate and promote climate change related studies and applications. Similarly, the ecological models developed predict the impacts of climate change on major forest tree species distributions, providing a scientific basis for impact assessments, identification of the most vulnerable species and populations, and developing adaptive strategies. Recommendations developed from the integration of climate and ecological model predictions with observed interactions between forest management practices and climate change at pilot sites has enabled optimization of forest management practices for adaptation to climate change. Web-based scientific tools, including interactive climate models, and Google map based climate and bioclimate envelopes (suitable climate ranges) will allow stakeholders and policy makers to easily access up-to-date scientific information for decision-making processes. The project has also improved the understanding of the impacts of climate change on ecosystems and forests, and enhanced the scientific communities' awareness of the potential changes in climate throughout the region. A network that connects scientists, forest managers, and policy makers has facilitated information sharing and knowledge transfer through workshops, field visits, and exchange of personnel (particularly from China to western North America). Lastly, this project has increased the level of coordination in forest management responses to climate change, thereby increasing the resilience of natural forests, plantations, and forest-dependent communities, while facilitating forest rehabilitation in the Asia-Pacific region.

Chapter 1 -- Reviews of existing science and policy

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1.1 Background

The purpose of this project segment was to review and analyze the existing science and policy related to climate change and forestry in the Asia-Pacific region. These reviews ultimately helped to steer the other project components and add context to the project as a whole, ensuring that research was novel, fit within the existing scientific and policy frameworks, and provided the necessary background information and tools to allow for the project's results to be seamlessly integrated into the existing contexts of forest management and climate change adaptation.

1.2 Methodology

Similar methodologies were used in the science and policy reviews. These methods are described in the following subsections.

1.2.1 Science Review

A review of scientific literature relating to climate change and forests in the Asia Pacific was conducted (See Appendix 1.1). To find existing information related to the effects and interactions that have occurred, or may occur, as a result of climate stressors or impact pathways, search engines were used to find relevant articles and research results, including Web of Science, Google Scholar, Science Direct, Research Gate and Scirus (which has since 'retired' from service).

Figure 1.1 provides examples of some of the search terms used for finding relevant scientific literature; it does not represent an exhaustive list of all search terms. Figure 1 illustrates how scientific literature searches were conducted to eliminate irrelevant information, and focus on research that best supported the objectives of this review and the project as a whole. All search engines were used in searching for all terms, and combinations of terms were used such that there was at least one of each: region or country, pathway or impact, and forest/vegetation element included in each search result – as indicated by the 3 table axes in Figure 1.1.

Search terms related to the region, impact pathways, and forest elements included – but were not limited to – those listed in Figure 1.1. For instance "Asia-Pacific", "Asia Pacific" and "Pacific coast" were used as regional search terms in addition to those listed in the figure; and specific species of economic importance such as Chinese fir (*Cunninghamia lanceolata*), Douglas-fir (*Pseudotsuga menziesii*) and eucalypts (e.g., *Eucalyptus regnans*) were used as region-specific vegetative search terms. A total of 213 pieces of literature were included in the review of science related to climate change and forestry in the Asia-Pacific. This existing research was used to identify common themes that can be used to drive forest management in a changing climate.

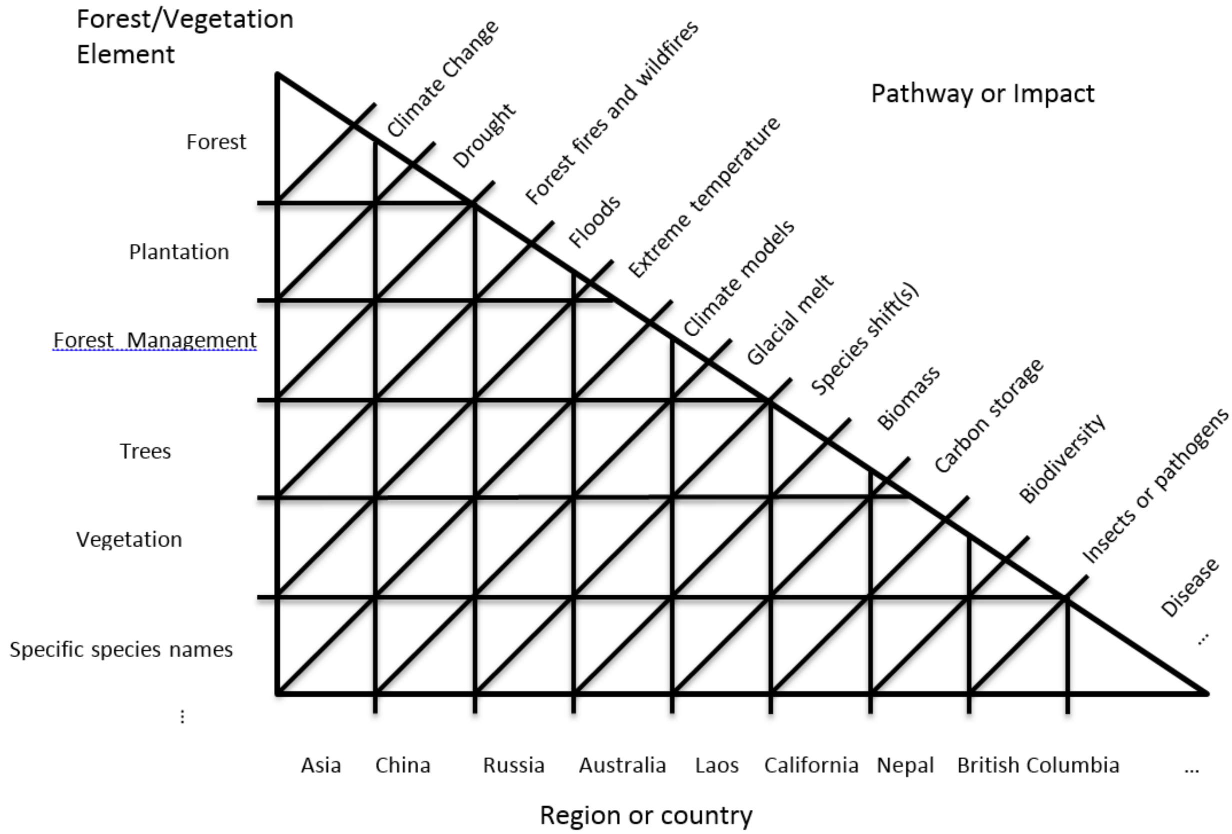

Figure 1.1. Examples of search terms used in finding scientific research relevant to climate change impacts and adaption in forests of the Asia-Pacific region. Note: Neither the lists of variables nor their intersections represent an exhaustive account of search terms.

1.2.2 Policy Review

For the policy review (See Appendix 1.2), the global policies/legislation, and those of each Asia-Pacific country, region or jurisdiction, were searched using terms such as "forest" and "climate change". Policies, agreements and relevant protocols were then included based on their relevance to forest management, impacts and adaptation in relation to any of the numerous aspects of climate change identified in the scientific review. Some policies or agreements spanned multiple jurisdictions (such as the Kyoto Protocol, or the Western Climate Initiative) and were included, along with unilateral or local policies and legislation, in an analysis of their relevance to climate change impacts and adaptation in forests of the Asia Pacific region.

Both the science and policy reviews present analyses and recommendations to assist the other project components, and to help steer forest resource management in a direction that ensures long-term forest sustainability in the changing climate of the Asia-Pacific.

1.3 Major Findings

Some of the major scientific findings related to the impacts (or outcomes) of climate change on forests of the Asia-Pacific included:

- Shifts in species ranges northward and upward (in terms of altitude).
- The selection of, and succession to, new species in forest ecosystems.
- Increases in the number and intensity of droughts in mid-latitudes.
- Increases in precipitation in the tropics and far north latitudes.
- Dry seasons will become drier and wet seasons will become wetter.
- There are anticipated changes in seasons – when they begin and when they end – throughout the region that have already been noted in some areas through changes in the timing of budbreak, etc.

Drought is an important aspect of a changing climate that is also linked to outcomes such as:

- further species shifts
- reduced tree germination and increased mortality
- insect outbreaks and wildfires
- reduced overall forest health

Despite the diverse scale in approaches reviewed, and the economic, social, climatic, and biological diversity that exists between jurisdictions or regions of the Asia-Pacific, a number of common themes emerged, which are out-lined below.

- Forests are effective carbon sinks, and forests in the Asia-Pacific are said to contain some of the world's largest carbon stores on an area basis.
- Sequestration of carbon by forests is considered permanent when viewed on a 100 yr time-scale.
- Long-lived forest products provide long-term carbon storage and therefore options for management and adaptation.
- Land-use, land-use change, and forestry emissions of greenhouse gases (GHG) are generally considered independently from other GHG emissions in reporting policies and emission inventories.
- Market-based cap and trade schemes are being used to create new forest valuation systems.
- Biomass is generally viewed as a carbon neutral fuel source.
- Preservation and conservation are considered key in effects management and adaptation.
- Managing forests to be more like natural forests increases both carbon storage and forest resilience to climate change.
- Forests can be managed for a changing climate using many of the same instruments that are used for sustainable forest management.
- There exist numerous co-benefits to climate change driven management (e.g. air quality, biodiversity, economic growth).
- GHG reduction can occur without economic sacrifice.
- Community management can be used to maximize forest "value".
- Mitigation and adaptation activities require new trade relationships and international coordination.

- Some contradiction exists as to who has their own strategies, whether or not strategies will be effective, and what the actual commitments are in terms of sustainable forest management.
- Climate change represents not just a liability, but also an opportunity, for forestry related activities.

In terms of the sequestration of carbon by forests, there were a number of notable themes and agreement within the literature:

- Aboveground biomass increases towards the equator.
- Belowground biomass increases towards the poles.
- Northern boreal and temperate moist forests have some of the largest carbon stores (globally).
- Older trees store more carbon, whereas younger trees take up more carbon.
- Carbon declines with the number of single species rotations.
- Carbon increases with increased species diversity.

1.4 Discussion: contributions, impacts and potential applications

Overall, the common themes that emerged were used to derive recommendations for forest management and policy development in the Asia-Pacific. These recommendations will assist in climate change mitigation and adaptation while preserving the value of forests, and the economic, social and environmental services that they provide.

Some of the final management recommendations that emerged from the scientific analysis include:

- The planting of mixed age and mixed species stands.
- Using a mix of species-specific rotations if necessary.
- The maximising of co-benefits (such as air quality, or non-timber forest products at the local level).
- The fertilising of managed forests only when soils are low in N or P.
- The use of prescribed burns to reduce fire risk.
- The monitoring of changes occurring within forests using a common set of indicators (e.g. bud break).
- Keeping all plans flexible, adaptable, and diverse in the face of climate uncertainty.

Some of the final recommendations that emerged from the policy analysis included:

- The development multilateral policy mechanisms.
- The accommodation of complexities and uncertainty - in both trade relationships and science.
- A focus on all emissions, not just GHG to allow for co-benefits in terms of human and environmental health.
- A balance between forest products and forest services within policy measures.
- The development of, and preference for, policies that are inherently adaptable and flexible due to the evolving state of our scientific knowledge.

1.5 Summary and Conclusions

The scientific review that was completed in the summer of 2013 includes the basic science of climate change and what the Asia-Pacific may expect. This review also discusses the major economic species and their roles under climate change impacts or mitigation measures. Forest management tools are also discussed in an Asia Pacific context. This report provides background for all other project endeavors. Overall, the review found that forests of the Asia Pacific present unique challenges and opportunities in light of climate change. For example, some forests in the region, such as the Eucalyptus forests of southeast Australia, or the boreal forests of northwestern North America, have immense carbon storage potential in their above- and below-ground biomass, respectively; whereas China's Chinese fir populations present a challenge when planted in homogeneous single-species stands from both a carbon sequestration and forest management perspective. Therefore, new ways to view forests and how we manage them can turn these challenges into opportunities, which are critical during strategic planning processes. Although forests of the region are faced with increased temperatures, increased frequency of catastrophic fires and storms, increased pest and disease outbreaks, and overall niche or habitat shifts, these forests are resilient; and through appropriate management strategies the region's forests can not only aid in climate change mitigation, but also help provide resources for the people that depend on them.

The policy review accumulated information on various policy measures in the Asia-Pacific region that have been implemented to either adapt to, or mitigate, climate change from a forestry perspective. Some policies may be specific to forest management, while others contain only brief reference to forests in terms of biomass energy or carbon sequestration. These policies were summarized and critically analyzed for their potential implications in a broader context in order to mitigate and manage climate change in the region. The review, also completed in the summer of 2013, found that forest and climate policies are diverse and often geared to the jurisdiction in which they are developed. However, efforts were made to summarize these similarities and frame these policies in terms of the political forces that developed them, while scientifically evaluating them to determine whether or not they are capable of achieving their expected goals.

Overall, the future of forests in the Asia-Pacific is bright, even in light of climate change. However, our ability to maintain the services that these forests provide depends on our ability to develop and execute both policies and management programs that are adaptable and based on sound science.

Chapter 2 -- ClimateAP – A high-resolution climate model for Asia Pacific

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2.1 Background

With a rapidly growing need for climate change related studies and applications, the demand for high-resolution and high-quality spatial climate data is high (Hamann *et al.*, 2013). Historical climate data is necessary for understanding the relationships between climate variables and plant performance, including their health and productivity. It is also essential for building climate niche based models for ecosystems and their components (McKenney *et al.*, 2011, Wang *et al.*, 2012c). These models are widely used to assess the impact of climate change, and to formulate adaptation strategies. For modelling the plant-climate relationships, climate data are required to represent the climatic conditions as accurately as possible to the real climate conditions where the plants or ecosystems reside (Hamann & Wang, 2006, Rehfeldt *et al.*, 2012a).

The climate data from weather stations are the most accurate and reliable. However, as the number of weather stations is limited, the locations of interest are usually far away, and have considerably different climate conditions from weather stations (Daly *et al.*, 2007, Hijmans *et al.*, 2005). 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 interpolated climate data is often not accurate enough.

The ANUSPLIN software developed by at the Australian National University using thin plate smoothing splines improved the interpolation, and it has been widely used. For example, WorldClim hosts gridded climate data for the entire globe using this approach (Hijmans *et al.*, 2005). However, ANUSPLIN is still a purely statistical approach and its accuracy is limited for areas 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 currently available. Interpolated climate data are available for the United States and some other regions including China.

In addition, although the availability of climate data has considerably improved during the last decade, some challenges still remain for non-meteorological users. For example, obtaining the climate data for locations of interest is not trivial work. It requires specific software and knowledge of Geographic Information System (GIS) to process the data. Particularly, climate data for historical and future periods are from different sources and with different formats, at various resolutions and different climate variables. Climate data generated by meteorologists often lack climate variables relevant for biological applications.

In order tackle the above challenges, several climate databases and tools have been developed including the ones developed by McKenney *et al*. (2011) and Rehfeldt *et al.* (2012b) using ANUSPLIN for North America. Users can submit coordinates files for specific locations to request climate data from them. The web-based Climate Wizard Tool (Girvetz *et al.*, 2009) covers the entire world and allows users to acquire climate data for any location. However, there is no downscaling involved, and it is not time effective to obtain climate data for multiple locations. ClimateBC is also one of these tools, and has been widely used for its effectiveness in downscaling, including both historical years and future periods, and user-friendly interface (Wang *et al.*, 2006a). ClimateBC was initially developed for western Canada and was, later on, expanded to ClimateWNA to cover western North America (Hamann *et al.*, 2013, Wang *et al.*, 2012b). Along with expansion in coverage, its functionality has also been enhanced by adding a time-series function and more derived climate variables. The objective of this study was to develop ClimateAP to cover the Asia-Pacific, and to further improve the functionality of this tool.

2.2 Data and Methods

2.2.1 Baseline data

ClimateAP uses the best available 30-year-normal monthly climate data as the baseline data for the reference period 1961-1990. Our first choice was the PRISM data for the reasons mentioned above. The PRISM data have clear advantages over other products in reflecting rain shadows, coastal effects, orographic lift, and temperature inversions over topographically delineated "facets" (Daly et al., 2002, Daly et al., 2008). However, the PRISM monthly data are only available for China and Mongolia. Therefore, we used the monthly climate data from WorldClim (Hijmans et al. 2005) for the rest of the region. The baseline climate data were provided at the resolution of 0.25 x 0.25 arcminute (about 4 km). The climate variables obtained from these data sources included three primary climate variables: monthly minimum temperatures (Tmin01, Tmin02, …, Tmin12), monthly maximum temperatures (Tmax01, Tmax02, …, Tmax12), and monthly precipitation (Pre01, Pre02, …, Pre12). The mean elevation of each grid cell was also included.

2.2.2 Historical climate data

We used the monthly temperature and precipitation data for 1901-2012 (version: CRU TS 3.21) generated by the Climatic Research Unit at the University of East Anglia (Mitchell & Jones, 2005). The original data were developed based on anomalies relative to the reference period 1961-1990, but absolute values were delivered for each individual years at the resolution of 0.5 x 0.5° ((Mitchell & Jones, 2005). To apply the delta downscaling approach (to be described below) in ClimateAP, we converted the data back to anomalies for each year by subtracting 1961-1990 normals.

2.2.3 Future climate data

The climate data for future periods were from General Circulation Models (GCMs) from the MCIP5 project in the IPCC Fifth Assessment Report (IPCC, 2014) downloaded from *http://cmip-pcmdi.llnl.gov/cmip5/*. GCM data are available at various spatial resolutions, ranging from 0.75 x 0.75° to 2.85 x 2.85°. We interpolated the GCM data to the resolution of 1 x 1° using bilinear interpolation for the ease of integration into ClimateAP. Two emission scenarios (RCP 4.5 and RCP 8.5) and fifteen

GCMs (Taylor *et al.*, 2012) were included in ClimateAP. Similar to the historical data, we converted future monthly values into two parts: the baseline values for the 1961-1990 normal period, and anomalies of the future period relative to the baseline period, for the purpose of downscaling using the delta approach described below.

2.2.4 Downscaling of the baseline climate data

We used a combination of bilinear interpolation and dynamic local regression approaches to downscale the baseline monthly grid data (4 × 4 km) to scale-free point data. Instead of applying the midpoint values of each grid cell to all points within each cell, we used bilinear interpolation method to interpolate values between midpoints of the four neighbor grids.

After the grid climate data and corresponding elevations were interpolated into continuous surfaces, we applied a dynamic local linear regression to estimate lapse rates for the location of interest to account for elevational effects. ClimateAP retrieved monthly climate data and elevation values from 9 of the closest neighbors for a given location, and calculated differences in climate variables and elevation between all 36 possible pairs of the 9 data points. A simple linear regression of the differences in a climate variable on the difference in elevation allowed the estimation of the lapse rate for the climate variable at a specific location. A lapse rate was estimated for each of the 36 monthly primary climate variables at each location of enquiry

2.2.5 Integration and downscaling of historical and future climate data

We integrated and downscaled both historical and future monthly climate data with a delta method following Wang et al. (2012). Historical and future monthly climate anomaly grids were first interpolated to continuous surfaces using bilinear interpolation at run-time to avoid step-artifacts at grid boundaries. The interpolated anomalies were then added onto the downscaled baseline monthly climate normal data (scale-free) to arrive at the final climate surface at a desirable resolution or point data. With this approach, the original baseline portion (absolute values for the 1961-1990 normal period) of the historical data and future projections are replaced by scale-free climate data generated by ClimateAP. Because the baseline data generated by ClimateAP are at much higher accuracy than that of the historical and future projections, this process is supposed to improve the prediction accuracies for both historical and future climate data.

2.2.6 Calculated and derived 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 calculated many additional climate variables at run-time based on these primary climate variables.

In addition to the primary climate variables included in the baseline data and directly calculated variables, ClimateAP also derived many biologically relevant climate variables from monthly climate variables, such as degree-days, the 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. We developed functions using these climate variables calculated from daily climate data from weather stations as dependent variables and the monthly climate variables from the same weather stations as predictors.

2.2.7 Statistical evaluations of ClimateAP outputs

The accuracy of the climate variables generated by ClimateAP was evaluated against observations at weather stations. Observed monthly normals of the primary climate variables for the reference period (1961–90) were calculated based on the daily climate data from the 1,805 weather stations across the entire study area shown in Figure 2.1. The amount of variance explained by the ClimateAP outputs and prediction errors (prediction standard errors) were used to evaluate the accuracy of the climate variables generated by ClimateAP for the baseline data.

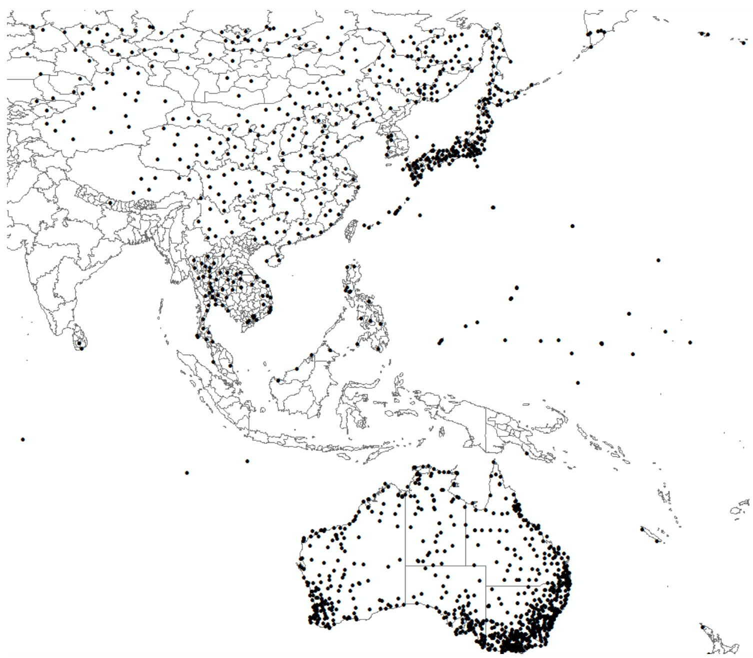

Figure 2.1. The distribution of weather stations that were used to derive the relationships between biologically relevant climate variables and monthly climate variables.

For the evaluations of the historical data downscaled with the delta approach, we compared the predicted values using CRU, GCMs, and ClimateAP against observations for the three primary monthly variables for the baseline normal period 1961-1990. As in the delta approach, the baseline part of the historical and future climate data were replaced by the scale-free baseline data generated by ClimateAP. The amount of improvement for the baseline data through this program would provide conservative evaluations for the predictions of historical and future climate data.

2.3 Results

2.3.1 ClimateAP interface and outputs

ClimateAP is a standalone MS Windows® application. It 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 or 4 x 4 km) to scale-free, and calculates seasonal and annual climate variables for specific locations based on latitude, longitude, and elevation (optional). The interface and the coverage of ClimateAP are shown in Figure 2.2. The output of ClimateAP include 208 directly calculated and dervied climate variables (Table 2.1).

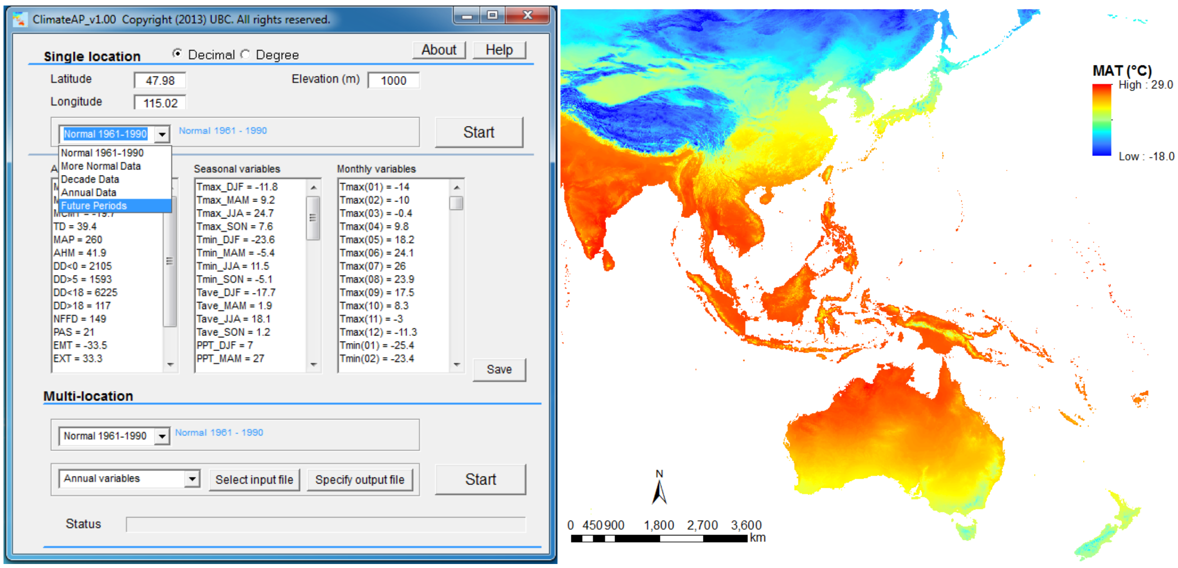

Figure 2.2 The interface and the coverage of ClimateAP

Table 2.1. 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 (°C)
	MWMT	Mean warmest month temperature (°C)
	MCMT	Mean coldest month temperature
	TD	Continentality, temperature difference between MWMT and MCMT (°C)
	MAP	Mean annual precipitation (mm)
	AHM	Annual heat-moisture index (MAT+10)/(MAP/1000))
	DD<0	degree-days below 0°C, chilling degree-days (°C)
	DD>5	degree-days above 5°C, growing degree-days
	DD<18	Degree-days below 18°C, heating degree-days
	DD>18	Degree-days above 18°C, cooling degree-days
	NFFD	The number of frost-free days
	PAS	Precipitation as snow (mm) between August in previous year and July in current year (mm)
	EMT	Extreme minimum temperature over 30 years (°C)
	EXT	Extreme maximum temperature over 30 years (°C)
	Eref	Hargreaves reference evaporation (mm)
	CMD	Hargreaves climatic moisture deficit (mm)
Seasonal	Tmax_DJF ~ SON*	Tmax for four seasons (°C)
	Tmin_DJF ~ SON	Tmin for four seasons (°C)
	Tave_DJF ~ SON	Tave four seasons (°C)
	PPT_ DJF ~ SON	PPT four seasons (mm)
	DD<0_ DJF ~ SON	DD<0 for four seasons
	DD>5_ DJF ~ SON	DD>5 for four seasons
	DD<18_ DJF ~ SON	DD<18 for four seasons
	DD>18_ DJF ~ SON	DD>18 for four seasons
	NFFD_ DJF ~ SON	NFFD for for four seasons
	PAS_ DJF ~ SON	PAS for four seasons
	Eref_ DJF ~ SON	Eref for four seasons
	CMD_ DJF ~ SON	CMD for four seasons
Monthly	Tave01 ~ 12	Average temperatures for Jan ~ Dec (°C)
	Tmax01 ~ 12	Maximum temperatures for Jan ~ Dec (°C)
	Tmin01 ~ 12	Minimum temperatures for Jan ~ Dec (°C)
	PPT01 ~ 12	Precipitation for Jan ~ Dec (mm)
	DD<0_01 ~ 12	DD<0 for Jan ~ Dec
	DD>5_01 ~ 12	DD>5 for Jan ~ Dec
	DD<18_01 ~ 12	DD<18 for Jan ~ Dec
	DD>18_01 ~ 12	DD>18 for Jan ~ Dec
	NFFD_01 ~ 12	NFFD for Jan ~ Dec
	PAS_01 ~ 12	PAS for Jan ~ Dec
	Eref_01 ~ 12	Eref for Jan ~ Dec
	CMD_01 ~ 12	CMD for Jan ~ Dec

*DJF – December, January and February; SON – September, October and November. The seasons in between are MAM – March, April and May, and JJA – June, July and August.

2.3.2 Effects of downscaling

The dynamic local linear regression effectively captured the local relationship of the temperature and precipitation changes along the elevation gradient. Figure 2.3 shows the relationships between the differences in temperature and precipitation, and the differences in elevation at a randomly picked location in a mountain area in China. At this location, the temperature inversion in a winter month was also reflected in the local dynamic regression. The slope of a regression line was used as the lapse rate for the climate variable involved. The lapse rates varied spatially and temporally for temperatures and precipitation.

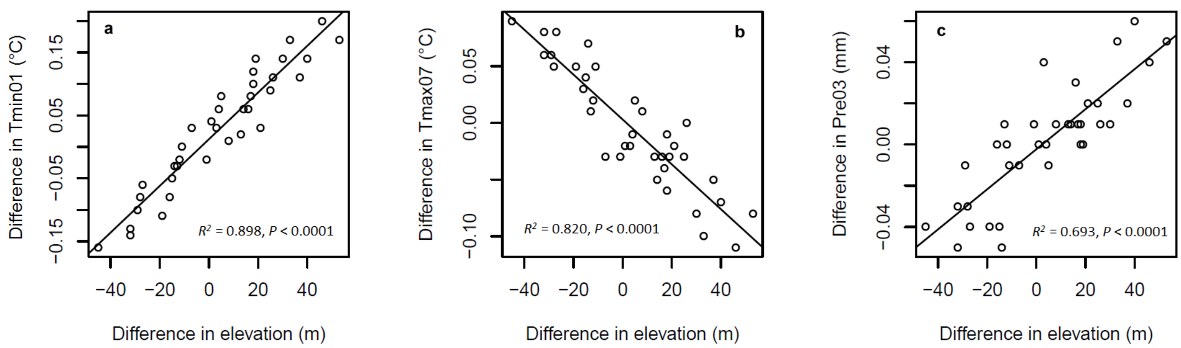

Figure 2.3. Relationships between differences in three monthly climate variables and differences in elevation captured by the dynamic local regression at a randomly selected location (latitude=48° and longitude=115°) in a mountain area. The three monthly climate variables include the minimum temperatures in January (a) and maximum temperature in July (b) and precipitation in March (c).

The effect of the downscaling can be visualized in Figure 2.4. The limitation of the moderate resolution of the grid data and power of the downscaling approach applied in ClimateAP are clearly shown on the maps.

The downscaling applied in ClimateAP had a small effect on the amount of total variance explained (less than 1%) for temperatures due to the large amount of total variation across the entire region, while it was larger for precipitation (0-12%). However, the improvement was substantial for prediction standard errors. The downscaling reduced prediction errors by 16-27% for monthly maximum temperatures and up to 60% for monthly precipitation. The improvement on monthly minimum temperatures was relatively poor (0-6%).

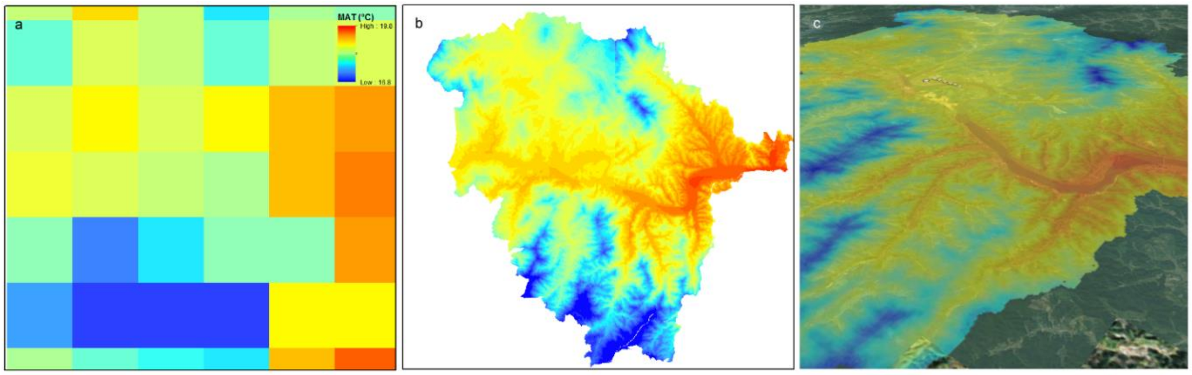

Figure 2.4. Illustration of the effect of downscaling approach applied in ClimateAP shown on the maps at a site in Fujian, China (centred at latitude = 26.789°N, longitude 117.820°E): a) mean annual temperature (MAT) of the baseline data at 4 x 4 km; b) downscaled MAT through ClimateAP (100 x 100 m); c) downscaled MAT (100 x 100 m) by ClimateAP and overlaid on a satellite geographic image.

The amount of variance in observed climate variables explained by ClimateAP predictions were very high. They varied between 97.3 and 99.3% for monthly minimum temperatures, between 97.7 and 99.6% for monthly maximum temperatures, and between 81.6 and 93.9% for monthly precipitation (Table 2.2). The prediction standard errors were about 1 and 0.9°C for monthly minimum and maximum temperatures, respectively, and about 25 mm for monthly precipitation.

Table 2.2. The amount of variance in observed climate variables explained by ClimateAP predictions and their prediction standard errors.

Variable	Variance explained (%)*	Prediction standard error (°C)	Variable	Variance explained (%)	Prediction standard error (°C)	Variable	Variance explained (%)	Prediction standard error (mm)
Tmin01	99.2	1.4	Tmax01	99.6	1.0	Pre01	88.2	28
Tmin02	99.3	1.3	Tmax02	99.5	1.0	Pre02	85.2	30
Tmin03	99.0	1.2	Tmax03	99.4	0.9	Pre03	88.4	28
Tmin04	98.3	1.0	Tmax04	98.8	0.8	Pre04	84.8	24
Tmin05	97.3	1.1	Tmax05	97.7	0.9	Pre05	89.1	23
Tmin06	97.9	1.0	Tmax06	98.2	0.9	Pre06	92.4	24
Tmin07	98.2	1.1	Tmax07	98.6	0.9	Pre07	93.7	22
Tmin08	98.3	1.0	Tmax08	98.9	0.7	Pre08	93.9	22
Tmin09	97.8	1.0	Tmax09	98.4	0.8	Pre09	91.9	24
Tmin10	98.0	1.1	Tmax10	98.8	0.8	Pre10	86.5	29
Tmin11	99.0	1.1	Tmax11	99.3	0.9	Pre11	85.6	23
Tmin12	98.6	1.3	Tmax12	99.3	1.0	Pre12	81.6	27

*ClimateAP predictions all exceeded the significance level of $P < 0.0001$.

The relationships between predicted and observed climate variables are demonstrated in Figure 2.5 for the minimum temperature in January, maximum temperature in July, and precipitation in March. The predicted climate variables were strongly and linearly correlated with observed values.

Interestingly, prediction errors were relatively larger in cooler regions for minimum temperature in January. However, this did not occur for maximum temperature in July, where larger prediction errors occurred in the mid-range of the temperature. For precipitation in March, the linear relationship was relatively weak compared to that for temperatures.

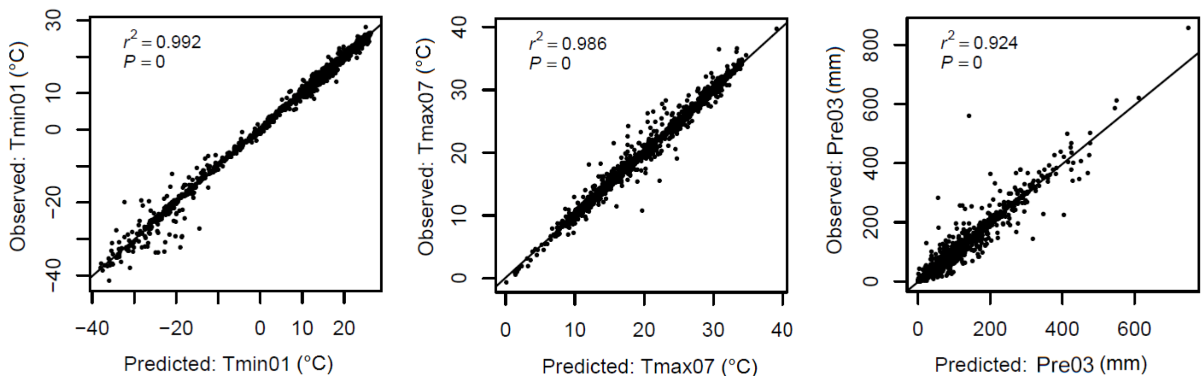

Figure 2.5. The relationships between observed and predicted climate variables using ClimateAP. The three climate variables are minimum temperature in January (Tmin01), maximum temperature in July (Tmax07) and precipitation in March (Pre03).

2.3.3 Accuracies of derived climate variables

The fits of the piecewise and nonlinear functions were extremely good for all derived climate variables. Three of the 60 fitted curves are shown in Figure 2.6 for degree-days below 0°C, degree-days above 5°C, and number of frost-free days in January.

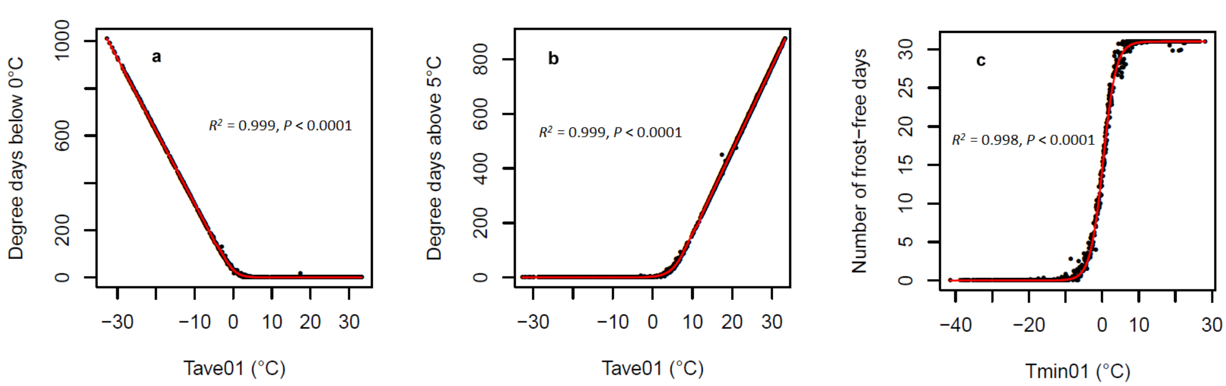

Figure 2.6. Relationships between derived monthly climate variables and monthly climate variables for degree-day below 0°C, degree-day above 5°C and number of frost-free days in January.

Through comparisons between the climate variables derived from monthly climate variables and climate variables calculated using observed daily climate data, we found that the derived climate variables, including various forms of degree-days, the number of frost-free days, and extreme minimum and maximum temperatures, were highly accurate based on the amount of variance explained and the prediction errors listed in Table 2.3.

Table 2.3. The amount of variance in observed climate variables explained by ClimateAP derived variables and their prediction standard errors.

Variable	Variance explained (%)		Prediction standard error	
	Monthly	Annual	Monthly	Annual
DD<0 (°C)	94.4 – 99.9	99.8	0.5 – 8.2	21.7
DD>5 (°C)	98.7 – 100.0	99.8	3.2 – 27.2	97.9
DD<18 (°C)	99.3 – 100.0	99.8	5.2 – 13.9	73.4
DD>18 (°C)	99.2 – 99.8	99.9	5.0 – 10.8	41.5
NFFD (day)	90.5 – 99.8	98.5	0.5 – 1.6	7.1
EMT (°C)		99.3		2.1
EXT (°C)		86.5		1.5

*All derived climate variables exceeded the significance level of $P < 0.0001$.

2.3.4 Improvements of historical and future climate data

Improvements of ClimateAP output for historical and future climate data over the original CRU and GCM data for the baseline data (1991-1990 normals) are shown in Figure 2.7. On average over the 1805 weather stations tested, the prediction standard errors for CRU data were reduced by 0.5°C (31%) for monthly minimum temperatures, 0.8°C (47%) for monthly maximum temperatures, and 21mm (44%) for monthly precipitation. The amount of improvement for GCMs was even greater, as expected; it prediction errors were reduced by to 2°C (67%) for monthly temperatures and 35mm (56%) for monthly precipitation on overage.

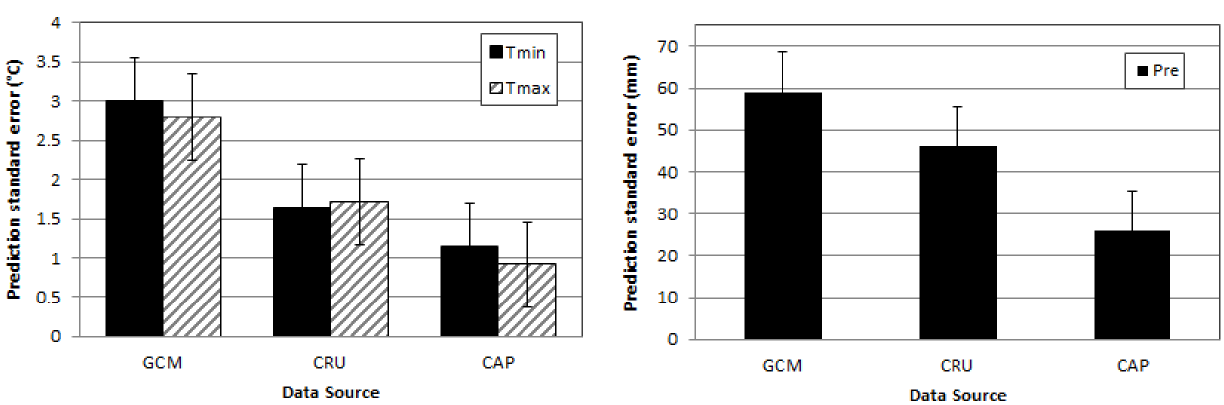

Figure 2.7. Comparisons in prediction standard errors among three data sources for the reference normal period 1961-1990: IPCC GCM predictions (GCM), Climate Research Unit (CRU) and ClimateAP (CAP) output. The error bars are standard errors indicating the variation among the 12 months.

Downscaled high-resolution data with improved accuracy were generated for the historical and future climate data by replacing the low-resolution baseline portion of the historical and future climate data with the high-resolution (scale-free) baseline data generated by ClimateAP, as illustrated in Figure 2.8. The amount of improvement should, at least, on average be equivalent to the amount of improvement for the baseline part, as mentioned above, without considering the effect of interpolation of the anomalies.

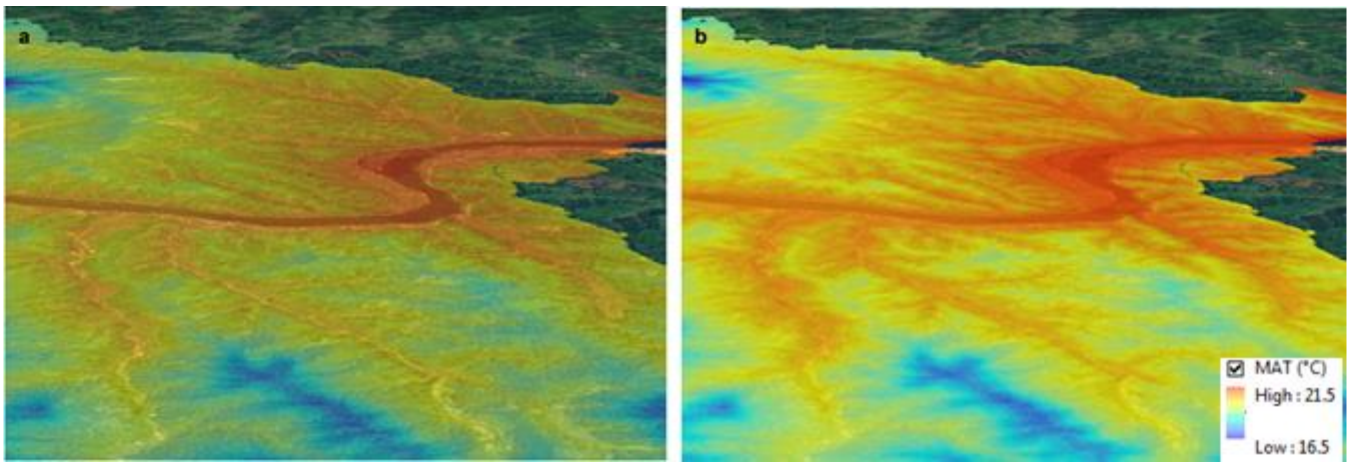

Figure 2.8. Demonstration of the high-resolution climate data (MAT) generated by ClimateAP at a site in Fujian, China (centred at latitude = 26.789°N, longitude 117.820°E) for the reference (1961-1990) (a) and a future period (2050s) (b). The future data layer was generated by adding the future anomaly layer onto the scale-free baseline data layer.

2.4. Discussion

2.4.1 Downscaling and prediction accuracy for the reference period

The downscaling approach, a combination of bilinear interpolation and elevation adjustment, applied in the predecessors of ClimateAP, ClimateBC and ClimateWNA, is effective for monthly temperature variables (Wang *et al.* 2006, 2012). In this approach, the elevation adjustment for each monthly climate variable is based on a global partial derivative function that reflects the lapse rate for the corresponding variable. The elevation adjustment is not applied to precipitation, because no significant partial derivative functions were developed for monthly precipitation variables due to their complicated spatial patterns. Due to the large spatial variation in the entire study area, we applied a dynamic local linear regression instead of the global partial derivative functions. The lapse rates of all climate variables for each specific location can be accurately captured, thus the downscaling of monthly precipitation variables has also been completed in this study.

Temperature inversion in winter months in some specific areas is considered difficult to model (Daly *et al.*, 2008, McKenney *et al.*, 2011). The dynamic local regression approach used in this study captured this phenomenon well as shown in Figure 2.3 for minimum temperature in January.

The accuracy of ClimateAP predictions for temperature is very high based on the amount of variance explained (>97%), suggesting that the ClimateAP predictions for temperature variables can accurately capture the spatial variation in this region. However, the prediction standard errors of ClimateAP (0.7 – 1.4°C) are larger than ClimateWNA (0.5 – 1.2°C) (Wang *et al.*, 2012b).

For precipitation, the accuracy of the prediction is much lower than for temperature in term of both the amounts of variance explained (82 – 94%) and prediction standard errors (22 – 30 mm) for monthly variables. Although the elevation adjustment is applied to monthly precipitation variables in ClimateAP, the accuracy is lower than that of ClimateWNA, in which elevation adjustment is not applied.

Slightly higher prediction errors in ClimateAP than ClimateWNA for both temperature and precipitation variables are probably attributable to the difference in the source of the baseline data between these two programs. As we mentioned in the introduction, PRISM data are more accurate than the data from WorldClim, particularly in precipitation variables according to Daly *et al.* (2008), and our experience. The majority of the baseline data in ClimateWNA is from PRISM, while more than 50% of the baseline data for ClimateAP were from WorldClim. In addition, the number of weather stations used for developing these baseline data is much greater in western North America than in the Asia-Pacific region.

2.4.2 Integration and downscaling of historical and future climate variables

ClimateAP integrates both historical and future climate data through a delta method. With this method, we split the absolute values of historical or future data into two parts: baseline data and anomalies. The baseline data are then replaced by the scale-free data generated by ClimateAP. The accuracy of the scale-free baseline data is much higher than that in the historical or future climate data, so this replacement not only increases the spatial resolution, but also considerably improves the accuracy of the historical (31-47% for temperatures and 44% for precipitation) and future climate data (67% for temperatures and 56% for precipitation). An example from a previous study (Wang *et al.*, 2012b), shows that the amount of error in temperature associated with baseline data in GCM projections can be up to 6°C on average due to their coarse resolution.

For the anomalies, they are bilinearly interpolated to point data at run-time in the program. This process may not considerably improve the predictions, but it smoothens steps across the original grid cells. However, the errors associated with the anomalies are supposed to be relatively small as they are less sensitive to topography, and their spatial variations are relatively easy to model in comparison to absolute values (Mitchell & Jones, 2005).

The delta method is also considered as a simple statistical downscaling method, and it appears to perform as well as sophisticated downscaling methods in producing mean characteristics (Fowler *et al.*, 2007), which are what we deal with in ClimateAP. However, the level of the improvement depends on the quality of the scale-free baseline data.

2.4.3 Applications

Climate is the primary factor regulating the geographic distributions of forest ecosystems and tree species (McKenney *et al.*, 2007, Rehfeldt *et al.*, 2012a, Woodward, 1987). It is also the main driver affecting the health and productivity of trees (Rehfeldt *et al.*, 1999, Wang *et al.*, 2006b) and other plants. Due to the difficulty in accessing climate data, research scientists have been using geographic variables, such as latitude, longitude, 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

Australia will not be valid in China. This is because the effect of elevation on climate is very different in different regions. In contrast, a relationship between the performance of a plant and climate variables will be applicable 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. Particularly, the time-series option in this tool allows users to generate climate data for multiple locations and multiple years with a few clicks, while obtaining the same amount of data by other means may take several months. Therefore, ClimateAP can be used for climate based experimental design, modelling climate niches for ecosystems and species, and population responses to climate.

Climatically based experiments will be more effective than geographically based in most cases. This is because the climate has a more direct effect on tree health and productivity than 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 is a good representation of the geographic distribution of this species. However, when plotting 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 clustered in a very narrow range of MAT (e.g., 19 sites are around MAT=3°C), while leaving a gap between -1.5 and 1°C. A climatically based experimental design would save 60-70% of the cost.

ClimateAP can also be used to generate climate surfaces. The output of ClimateAP is in a comma-separated-values (CSV) format, which 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. It is particularly useful to generate high-resolution climate maps for specific areas to develop management practice strategies that consider climate conditions.

Modelling climate niches for ecosystems and species requires climate data to be well matched with the actual locations of the vegetation data (Roberts & Hamann, 2012, Wang *et al.*, 2012a). The scale-free climate data generated by ClimateAP is suitable for meeting this requirement. In addition, the availability of a large number of calculated and derived biologically relevant climate variables will considerably increase the modelling power for such objectives.

2.4.4 Limitations

To our knowledge, ClimateAP is so far the best tool for generating high-resolution climate data for the Asia-Pacific. Its predictions can account for more than 97% of the total variation in temperatures and 82 – 94% in precipitation for the 1961-1990 normals. However, the standard prediction errors in term of absolute values are still considerably large, as they are 0.7 – 1.4°C for temperatures and 22 – 30 mm for monthly precipitation. This can potentially be much greater when examining specific locations. As well, these prediction errors can be even greater when the predictions are for specific years instead of the 30-year normals. The prediction errors are expected to be smaller in the regions with more weather stations than the regions where weather stations are lacking. The dynamic local elevation adjustment is an effective means of downscaling the baseline data. However, it is not able to correct the errors associated with the input baseline data or the anomalies of the historical and future climate data. In addition, despite ClimateAP's ability to generate spatial climate surfaces at very fine resolution or scale-free data sensitive to elevation gradients, the microclimate affected by aspect, slope, and vegetation types at micro-scale are not reflected in the predictions. Therefore, caution is required when interpreting the climate data at very fine spatial resolution.

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Chapter 3 – Climate niche models of five major forest tree species

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3.1 Background

Climate is the primary factor regulating the geographic distribution of forest tree species (Woodward 1987, McKenney and Pedlar 2003), which are adapted to a range of climatic conditions (i.e., often referred to as their "climatic niche"). Due to the slow rates of migration for long-lived tree species, unprecedented 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). Individuals or populations exposed to climate conditions outside their climatic niches will be maladapted, resulting in compromised productivity and increased vulnerability of forest ecosystems to disturbance such as insects and pathogens. Thus, matching forest tree species to their climate niches in a changing climate is critical in adaptive forest resource management. Modelling the climatic niches of forest tree species and projecting their shift in the future periods, therefore, are important essential steps in developing adaptive forest resources management strategies.

Bioclimate envelope models (i.e., also referred to as "ecological niche models") are built based on the relationships between the observed presence of a species (or a forest ecosystem) and values of climate variables at those sites. Since they rely on actual distribution of the target species, they model the realized niche (i.e., resulting from abiotic and biotic constraints, such as interspecific competition) as opposed to the fundamental niche (i.e., solely based on the species' abiotic requirements). However, it is important to emphasize that these models predict the shift in distribution of the climatic niche of a species (or a forest ecosystem) 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 (Levinson and Fettig 2012). Bioclimate envelope models have widely been used in North America (Hamann and Wang 2006, Rehfeldt et al. 2006, McKenney et al. 2007, Wang et al. 2012) and Europe (Araujo & New, 2007, Buisson et al., 2010, Lindner et al., 2014). However, related studies in the Asia-Pacific are somehow lacking, even though most of the world's forest plantations occurred in this region in the past years. This lack is partially due to insufficient vegetation data and limited access to high quality climate data.

Although digital distribution maps are available for a large number of species, present-absent data are lacking in the Asia-Pacific region. This limits the use of Random Forest to build the model. Random Forest is an ensemble learning method for classification and is considered one of the most powerful modelling tools. To overcome this limitation, we generated pseudo absent data (Elith & Leathwick, 2007), and applied it to multiple forests to cope with the unbalanced present-absent samples.

To address the uncertainty in future climate, most of the studies use either the averages (or ensembles) of climate change scenarios (i.e., the combinations of greenhouse gas emission scenarios and general circulation models (GCMs)) or a small number of climate change scenarios. The disadvantage of using the averages is that specific spatial and temporal patterns of each GCM are cancelled out. We followed the approach applied in Wang et al. (2012), and generate consensus projections using a large number of climate change scenarios.

In this study, we chose three major forest tree species in China including Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook), Masson Pine (*Pinus massoniana*), and Chinese pine (*Pinus tabuliformis* Carr.), and one major species, Douglas-fir (*Pseudotsuga menziesii*), in North America. We also chose one major forest tree species in Australia, Blue Gum (*Eucalyptus globulus*). Chinese fir and Masson pine are the two most important subtropical coniferous species in China. Chinese fir, in particular, occupies about 30% of all plantations in China and accounts for 25% of China's national commercial timber production, thus playing a major role in the environment, timber supply, and human society. Chinese pine is the most widely distributed conifer in North China, with a natural range that stretches from northeastern to northwestern China, between latitudes 31°00' and 44°00' N and longitudes 101°30' and 124°25' E. Douglas fir is one of the world's best timber producers and yields more timber than any other tree in North America. It has been successfully introduced to many countries, particularly in several European countries including Germany and Austria. Blue Gum, an evergreen broadleaved tree species, is one of the most widely cultivated trees native to Australia. It has four subspecies distributed in the South states, including Tasmania Island.

3.2 Data and methods

3.2.1 Vegetation data

Presence observations for Chinese fir, Masson pine, and Chinese pine were obtained from the digital version of Vegetation Map of China (1:1000,000) provided by "Environmental & Ecological Science Data Center for West China, National Natural Science Foundation of China"(link: http://westdc.westgis.ac.cn). A shape file of the distribution map was generated for each species by selecting the species and its mixture with other species. The shape file was then rasterized at the spatial resolution of 0.00833 arc minute (approximately 1 km). Each data point within polygons of presence was assigned as presence of the species.

Species data for Douglas-fir were from were assembled from a variety of sources due to the wide spread of this species. For British Columbia (BC), the species data were obtained from ecological plots managed by the BC Ministry of Forest, Land and Natural Resources. For the United States, tree species data were taken from U.S. Forest Service, Forest Inventory and Analysis plots (US-FIA). FIA data are recorded on a permanent sampling grid established across the conterminous United States at a density of approximately one plot per 2400 ha.

For Blue Gum, the presence observations were obtained from the Atlas of Living Australia (Atlas) (http://www.ala.org.au). The observations were aggregated from a wide range of data providers including museums, herbaria, community groups, government departments, individuals, and universities.

Pseudo absent point data for each species were generated for areas with no presence of the species within the range of the species distribution, and expanded by 200 km in each of the four directions if possible. The coordinates of the present and absent data points for each species were extracted into a comma-delimited spread sheet file for the generation of climate data.

3.2.2 Climate data

ClimateAP, developed in this project, was used to generate climate data across the region. For this study, we generated 66 annual and seasonal climate variables for the presence and absence point locations of the species for the reference normal period 1961-1990. Monthly climate variables were not considered, as the number of annual and seasonal climate variables was large enough. In addition, we did not want model predictions being bound to the climate conditions of a specific month.

For the predictions and projections of the geographic distribution of each species for the reference period (1961-1990 normal) and three future periods (2020s, 2050s and 2080s), gridded climate data were generated at the spatial resolution of 4x4 km for China and Australia. For future projections, the gridded climate data were generated for 12 climate change scenarios including six AR5 GCMs and 2 emission scenarios (RCP4.5 and RCP8.5) (Taylor 2012). The six GCMs include: ACCESS1-3, BCC-CSM1, CanESM2, CNRM-CM5, CSIRO-Mk3-6-0, and HadGEM2-ES (http://cmip-pcmdi.llnl.gov/cmip5/availability.html).

3.2.3 Statistical analysis

We used the R version (Liaw and Wiener, 2002) of Breiman's (2001) Random Forests (RF) algorithm to model relationships between climate variables for the reference period and the presence and absence of each of the four species. 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. Using the trees grown with the bootstrap sample, each of the independent observations in the OOB sample is classified (assigned to either presence or absence) and a model prediction error, called the OOB error (% of incorrectly classed observations), is calculated.

RF works best if the samples are relatively balanced between classes (Rehfeldt et al 2006). Our sample data were unbalanced with the number of absent data points being much greater than that of the present data points. One way to balance the samples was to randomly sample the absent data points to match the number of present samples. However, this might lead to a poor representation of the areas where the species are absent. We applied a multiple "forests" approach to build an ensemble of RF models; each model with built with randomly sampled absent data points to match the number of present data points while the present data remained the same. The final prediction was based on the composite prediction of the 10 individual model predictions.

RF generates importance values for each of the predictors. We used the importance values to optimize the model, and to identify the climate variables that are important in affecting the distribution of each species. We started the RF model with the entire 66 climate variables included, followed by a model with the least important climate variable removed. This process was iterated until only two climate variables (i.e., the least possible number of predictors) remained in the model. The optimal number of climate variables that produced best predictions was then identified in this process. To consider the unbalanced samples as mentioned above, the elimination of the least important climate variable was based on the average of the importance values across 10 forests.

The final RF models were built using the optimal combination of climate variables for each of the four species. The models were also optimized for the number of trees in each forest and the number of predictors selected at each node. We used 300 trees, which was more than adequate, for all species. The effect of the number of predictors selected at each node was minor, so we just used the default, which is the square-root of the number of climate variables.

The final RF models were then fed with the climate variables for the gridded data points to generate spatial predictions for each prediction or projection period for each of the five species for China, west North America or Australia. For the reference period, the frequency of predictions for presence of a species by each of the 10 forests was counted for each gridded pixel. For future periods, the frequency counting was at two levels; the first was among the 10 forests and the second was among the 12 climate change scenarios. We set it as "presence" if the number of predictions was equal or larger than 5, so that we only needed to count predictions of "presence" among the climate change scenarios to determine the consensus of the projections. Blue Gum was modelled at subspecies level, thus the frequency counting did not work, so we used the mode of predictions as the final outputs. The final outputs were then imported into ArcGIS (v10.2.1) to generate maps.

3.3 Results

3.3.1 Important climate variables and climate niches of the species

Through the removal of the least important climate variable from the RF model each time, we identified the best combination of climate variables for the RF model for each species. The change in the OOB error rate with the number of climate variables is demonstrated for Chinese fir in Figure 3.1. The level of change was not substantial when the number of climate variables was greater than 20. The 10 most important climate variables for each species are listed in Table 3.1.

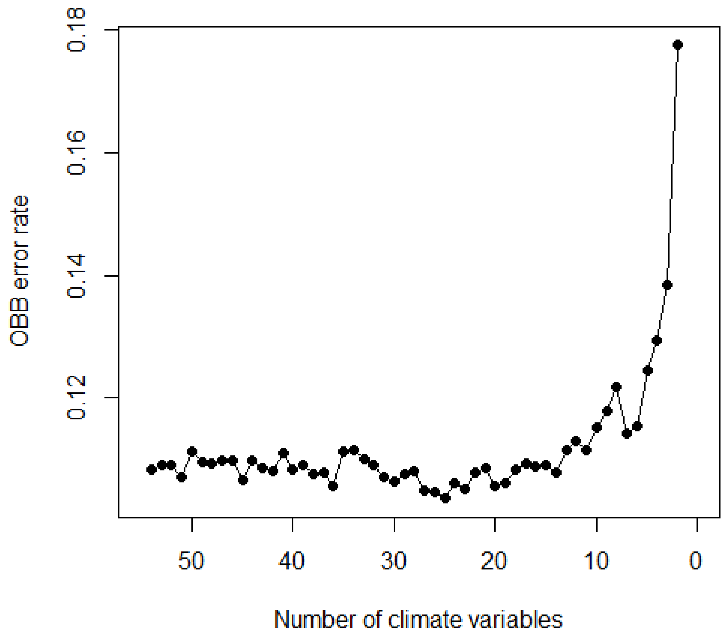

Figure 3.1. Changes in error rate of RF model prediction for out-of-box (OOB) samples with the least importance climate variable removed step by step.

Table 3.1. The top 10 important climate variables for each of the four forest species based on the importance values (Imp. value) generated from Random Forest model.

Chinese fir		Masson pine		Chinese pine		Douglas-fir		Blue gum	
Climate variable	Imp. value	Climate variable	Imp. value	Climate variable	Imp. value	Climate variable	Imp. value	Climate variable	Imp. value
PPT_mam*	40.6	TD	33.8	CMD_jja	39.9	Eref_son	47.7	PPT_djf	41.1
TD	35.6	PPT_mam	32.8	PPT_jja	37.8	PPT_djf	38.9	Eref_mam	32.1
Tmin_jja	34.6	CMD_djf	31.4	Tmin_jja	32.6	TD	38.4	PPT_jja	39.3
PPT_son	30.4	PPT_jja	26.9	TD	31.1	PAS_mam	38.1	Eref_jja	26.6
Tmin_djf	29.6	PPT_djf	22.9	DD5_son	25.4	Tmin_djf	37.8	TD	30.7
Eref_mam	29.1	DD5_jja	22.2	MAP	24.0	PPT_jja	37.0	CMD_djf	27.7
PPT_jja	28.9	Tmax_mam	22.0	MWMT	23.8	CMD_son	35.7	DD5_djf	26.6
CMD_son	27.8	CMD_son	20.5	CMD_son	23.7	PPT_mam	35.5	EXT	28.7
Tmin_son	27.7	Eref_jja	19.8	DD5_jja	23.1	PPT_son	33.9	PPT_son	26.5
DD5_jja	27.6	Tmin_jja	19.2	CMD	22.8	DD5_jja	32.7	Tmin_mam	27.5

*PPT = precipitation; Tmin = mean minimum temperature; Tmax = mean maximum temperature;
MAP = mean annual precipitation; EXT= extreme maximum temperature over 30 years;
Eref = Hargreaves reference evaporation; CMD = Hargreaves climatic moisture deficit;
MWMT = mean warmest month temperature; MCMT = mean coldest month temperature;
TD = the difference between MWMT and MCMT, also referred to as continentality;
DD5 = degree-days above 5°C, growing degree-days;
mam = March – May; jja = June – August; son = September – November;
djf = December - February

The overall accuracies of the models were high (> 90%) for all species modelled. The OOB error rate was higher for absence than for presence except for Blue Gum. This was expected as the sampling rate affects the error rate, and the sampling rate for absence was much smaller. For Blue Gum, the modelling was at the subspecies level, so that the sampling rate for presence was reduced compared to the sampling rate at species level. The climate niche for each species in terms of the most commonly used climate variables (mean annual temperature and precipitation) are also listed in Table 3.2.

Table 3.2. Model error rates and major climate profiles for the four major forest tree species

Species	Model error rate (%)			Mean annual temperature (°C)	Mean annual precipitation (mm)
	Presence	Absence	Overall		
Chinese fir	5.4	11.8	8.6	16.9 (9.2 ~ 22.6)	1637 (834 ~ 3062)
Masson pine	3.0	9.7	6.4	17.6 (6.4 ~ 23.5)	1553 (650 ~ 3199)
Chines pine	7.1	12.4	9.8	7.3 (0.4 ~ 14.7)	620 (228 ~ 1122)
Douglas-fir	8.6	9.8	9.2	6.0 (-1.7 ~ 16.1)	1029 (240 ~ 6510)
Blue Gum	9.7	6.8	8.1	12.0 (4.6 ~ 18.4)	887 (455 ~ 2928)

The composite predictions of the climate niches for each species are shown in Figure 3.2a, 3.3a, 3.4a, 3.5a, and 3.6a. The predictions from the 10 RF models using random samples of absence were in strong agreement for the vast majority of areas, while disagreement only occurred at margins of the climate niches for all five species. The predicted climate niches covered the current distributions of the species, but they also expanded beyond their current distributions. This was particularly true for Chinese fir; the area suitable for this species was much greater than the current distribution.

3.3.2 Consensus projections of climate niches for future periods

Some common features were shared among the consensus projections of the climate niches for future periods among the five species (Figure 3.2, 3.3, 3.4, 3.5 and 3.6). The 12 projections using different climate change scenarios were highly consistent among species for 2020s. However, the consistency declined for the future periods of 2050s and 2080s. This suggests that the uncertainty in projections of climate niches is relatively low for the near future. An upward shift in elevation of the projected climate niches was another common feature. The magnitude of the shift was substantial – up to 1100m by 2050s. Interestingly, no clear northward shift was projected, as is commonly expected, except for Douglas-fir. Blue Gum on the other side of the equator did show some level of southward shifting. The area size of the climate niches were projected to contract for Chines fir, Masson pine, and Blue Gum, while range expansions were projected for Chinese pine and Douglas-fir by 2050s (Table 3.2).

For Chinese fir and Masson pine in southern China, contractions in trailing edges (in the south) of their climate niches were projected (Figure 3.2 and 3.3) as expected. Surprisingly, the expansion of their climate niches in the leading edges (in the north) was nearly absent. For Chinese pine (Figure 3.4), the expansion of its projected climate niche was substantial (47% by 2050s) (Table 3.2). Interestingly, the expansion was westward instead of northward. The typical northward and upward shifts were projected for Douglas-fir.

For Blue Gum, the projected shifts in the future periods were southward and towards the end of the continent, resulting a considerable contraction of the suitable climate niche for this species (-24% by 2050s) (Figure 3.6 and Table 3.3). Projected changes in the area of the climate niches varied considerably among the subspecies of this species (Table 3.4). The climate niche of *E. globulus* subsp. *Pseudoglobulus* was projected to nearly disappear by 2050s. In contrast, the size of projected climate niche for *E. globulus* subsp. *globulus* was almost the same. The contraction for *E. globulus* subsp. *Bicostata* was also substantial (-50%).

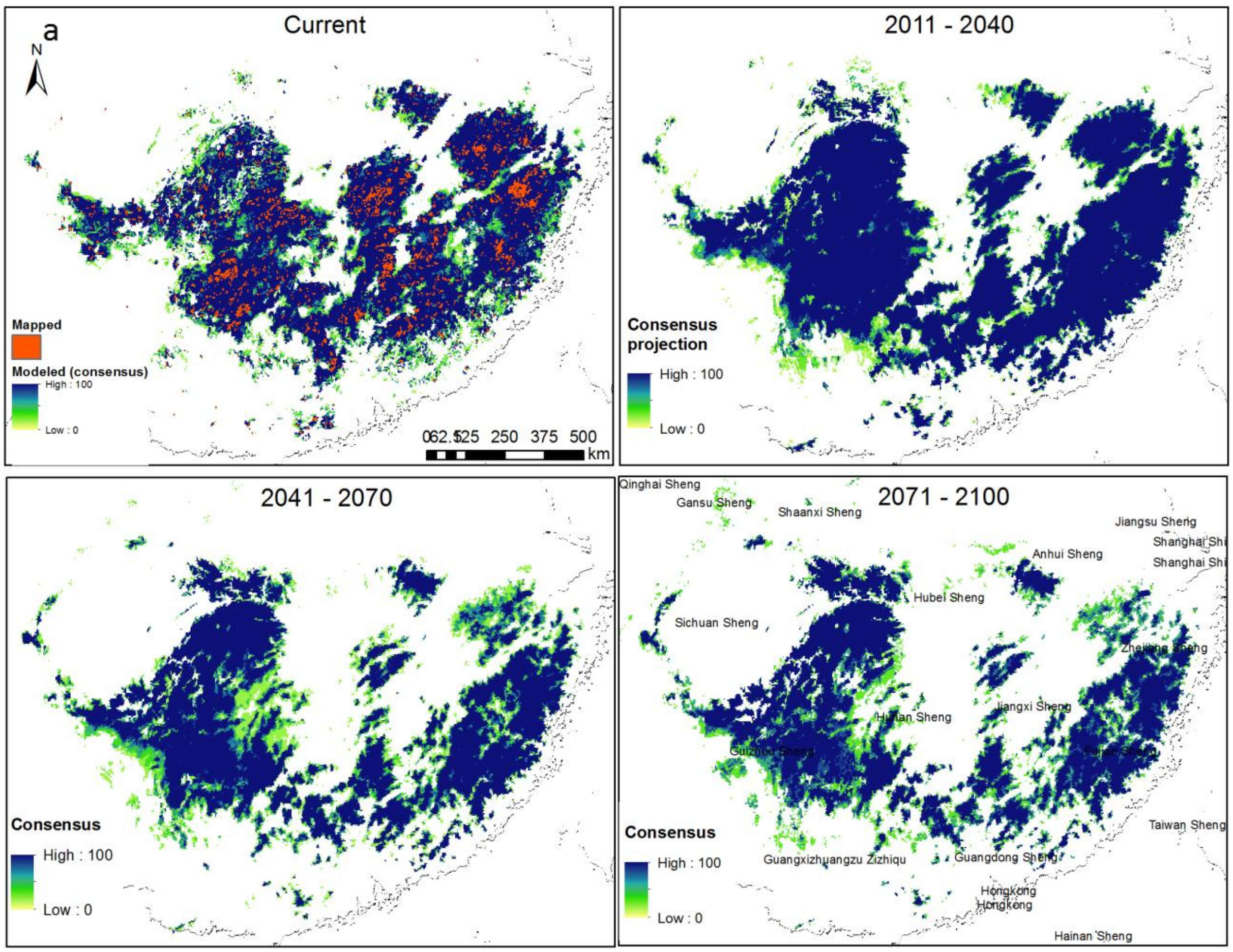

Figure 3.2 Geographic distributions of climate niche for Chinese fir based on composite predictions for the current (1961-1990) and consensus projections for the three future periods 2020s, 2050s and 2080s.

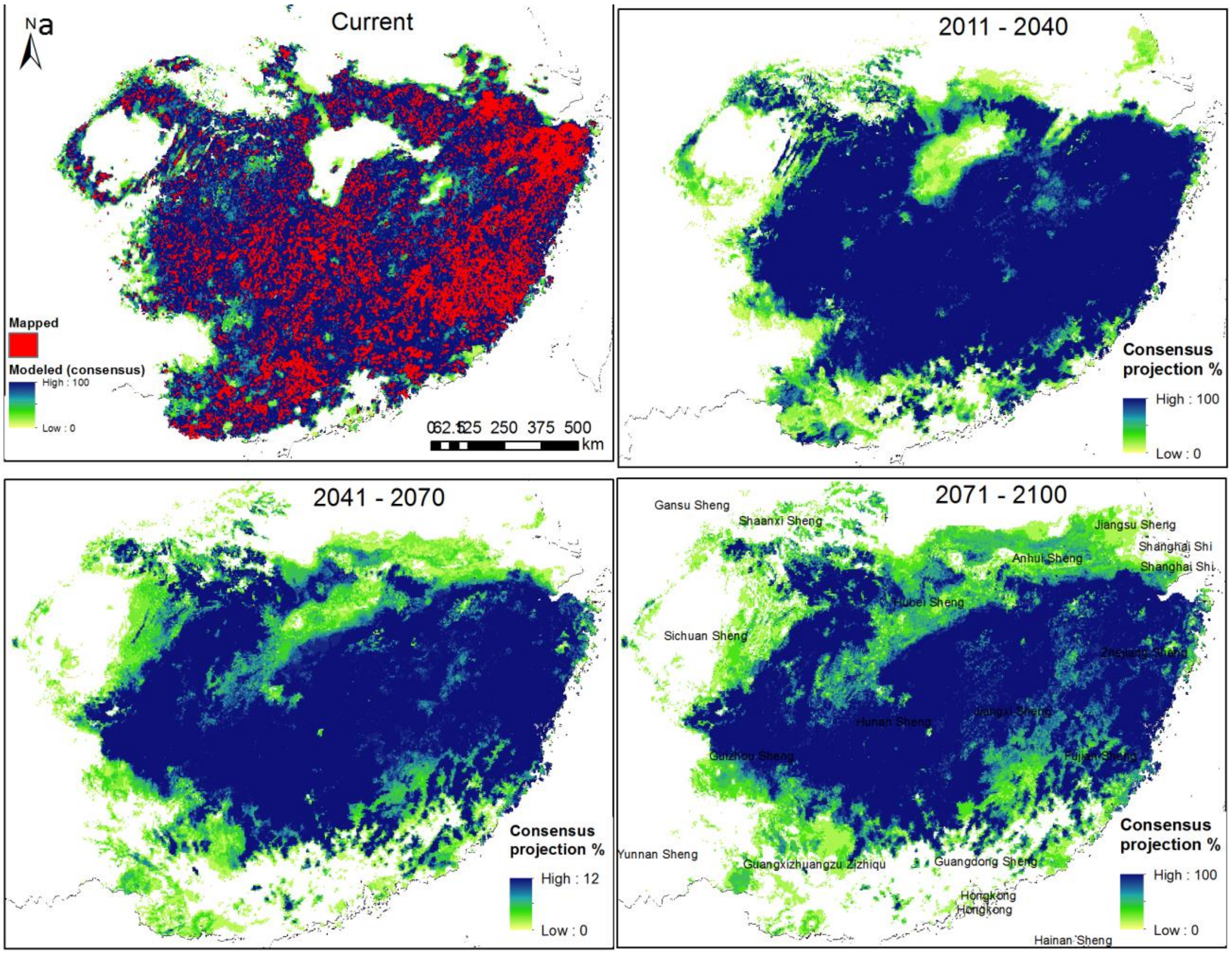

Figure 3.3 Geographic distributions of climate niche for Masson pine based on composite predictions for the current (1961-1990) and consensus projections for the three future periods 2020s, 2050s and 2080s.

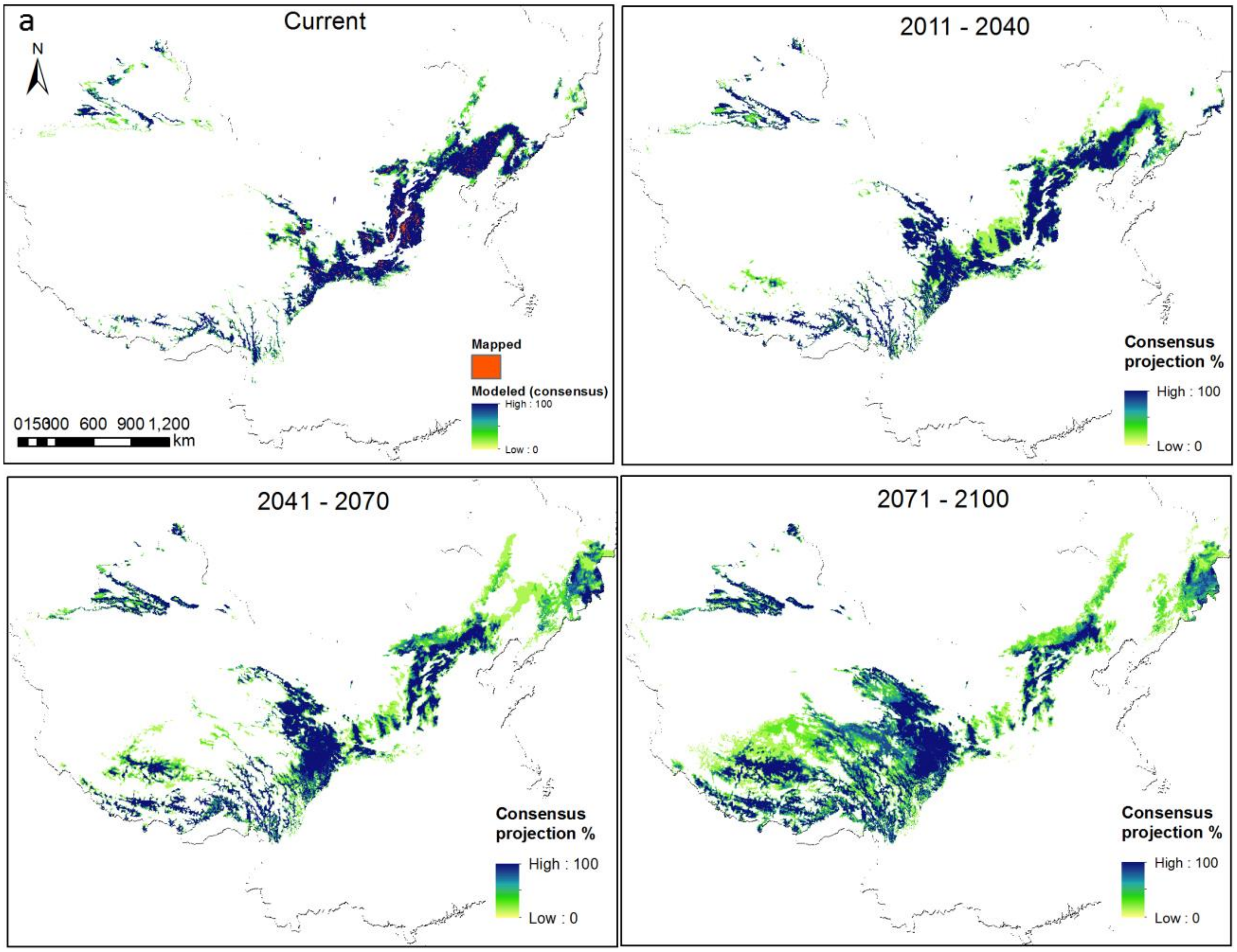

Figure 3.4 Geographic distributions of climate niche for Chinese pine based on composite predictions for the current (1961-1990) and consensus projections for the three future periods 2020s, 2050s and 2080s.

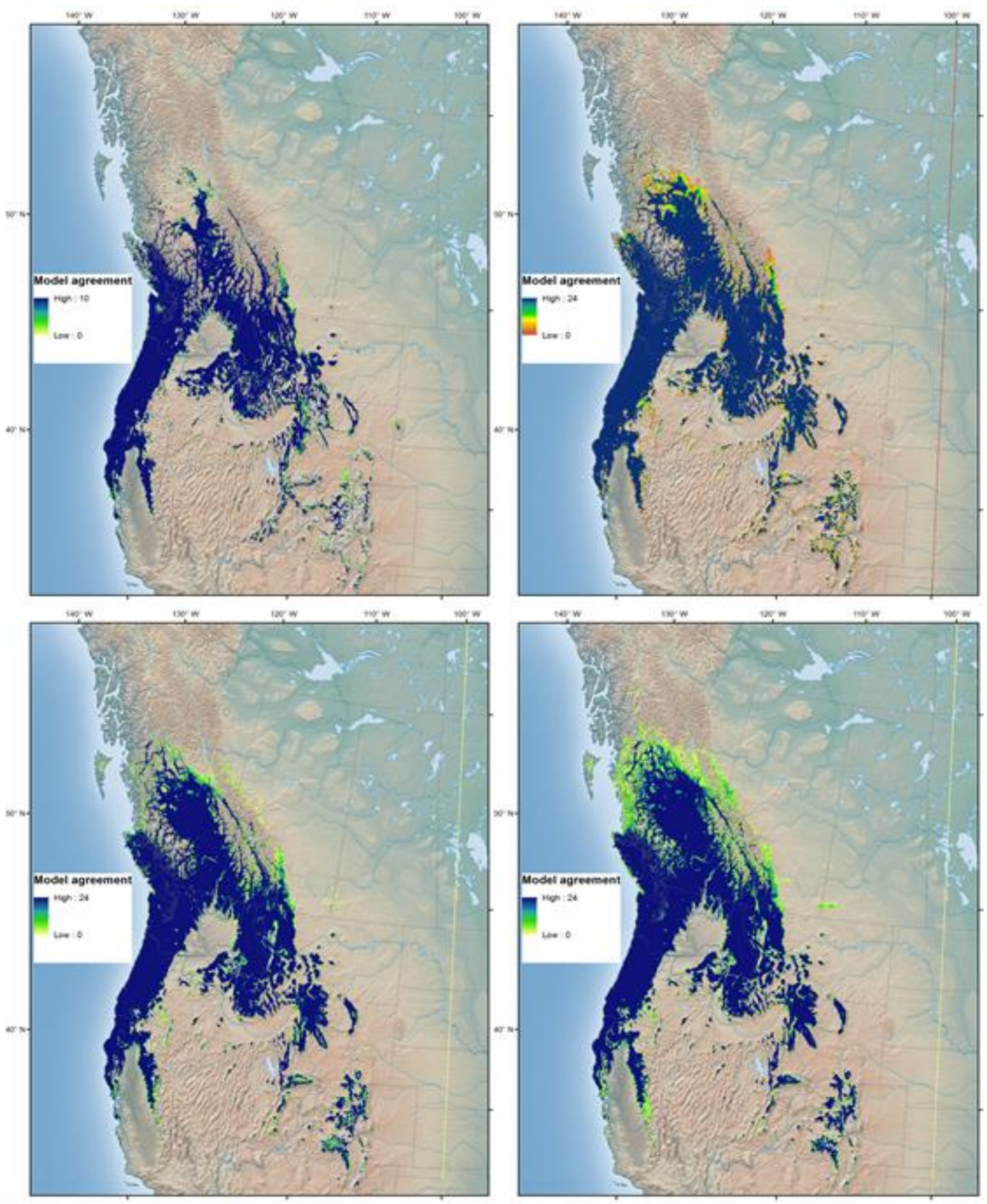

Figure 3.5 Geographic distributions of climate niche for Douglas-fir based on composite predictions for the current (1961-1990) and consensus projections for the three future periods 2020s, 2050s and 2080s.

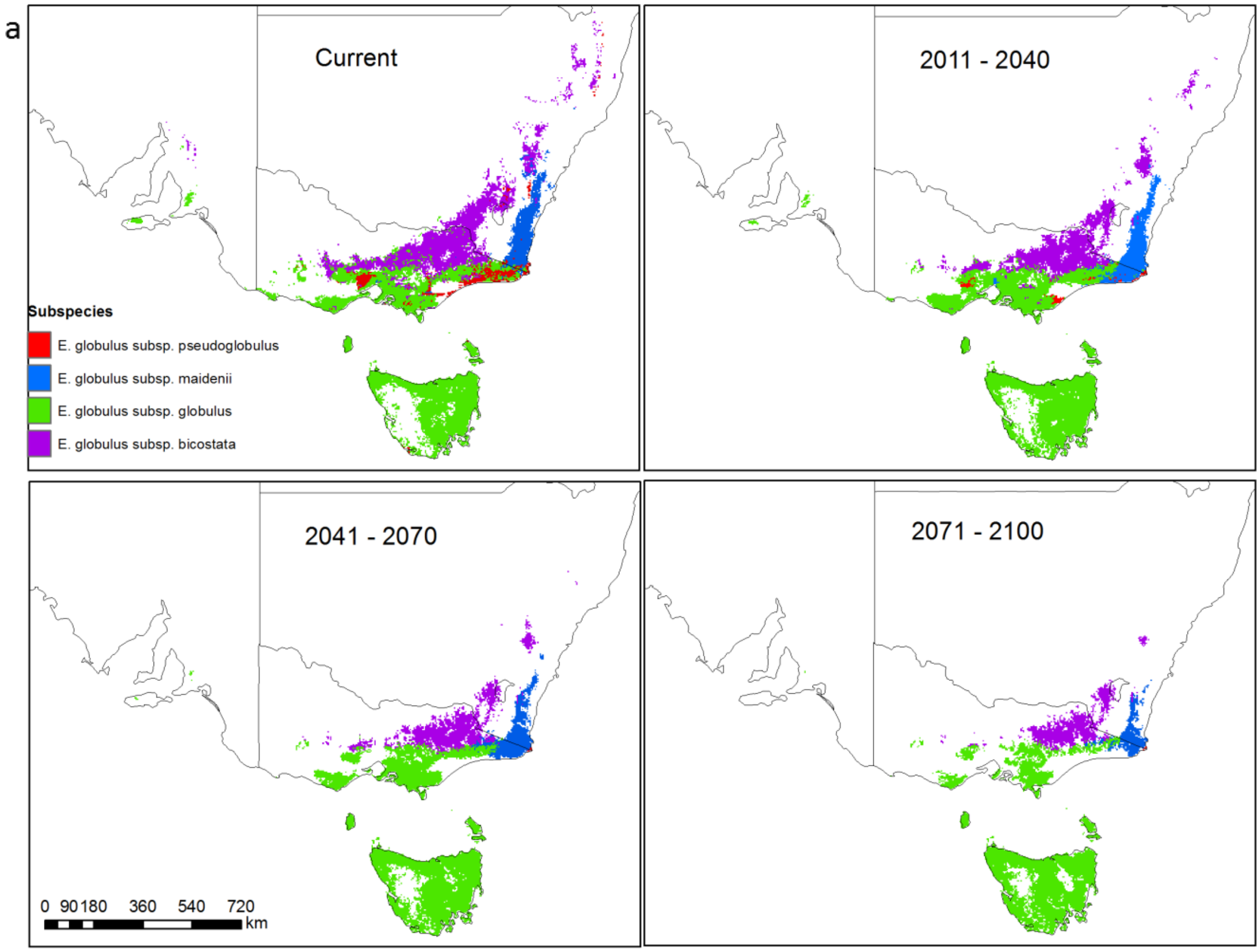

Figure 3.6 Geographic distributions of climate niche for the four subspecies of Blue Gum based on composite predictions for the current (1961-1990) and consensus projections for the three future periods 2020s, 2050s and 2080s.

Table 3.3 Changes in average latitude, longitude, elevation and areas of climate niches for each species by 2050s relative to the reference period 1970s.

Species	Latitude (°)	Longitude (°)	Elevation (m)	Area (%)
Chinese fir	0.1	-0.7	244	-34.2
Masson pine	0.4	0.5	61	-17.0
Chinese pine	-0.7	-5.6	1129	46.8
Douglas-fir	1.0	-0.6	130	39.4
Blue gum	-1.2	-0.1	3	-24.3

Table 3.4. Changes in average latitude, longitude, elevation and areas of climate niches for subspecies of Blue Gum by 2050s relative to the reference period 1970s.

Subspecies	Latitude (°)	Longitude (°)	Elevation (m)	Area (%)
bicostata	-6.8	-9.6	230	-50.7
maidenii	-0.9	-0.4	3	-10.9
globulus	-0.6	0.3	-1	-1.4
pseudoglobulus	-0.2	-2.1	-224	-99.0

3.4 Discussion

3.4.1 Climate niches of the species

The climatic niches modelled based on multiple Random Forest models facilitate a credible mapping of geographic distributions of the suitable climate niches (Figure 3.2 ~ 3.6), and defining of the ranges of temperature and precipitation of the climate niches (Table 3.2) for the five important forest tree species including Chinese fir, Masson pine, Chinese pine, Blue Gum, and Douglas-fir. The maps of climate niche distributions included both the areas the species currently occupy and areas with climatic conditions suitable for the species, but where they are absent due to various factors including physical barriers, adaptational lags and/or human interference. These maps will be particularly useful for afforestation involving these species in the areas where they are not established.

It is important to keep in mind that climate niches models predict the realized climate niche rather the fundamental climate niche of a species. The realized climate niche represents favourable climate conditions for the species, and it is a result of long-term migration, local adaptation of the species, and its interactions with other species. In other words, there are several reasons that a species occurs only within a range of climate conditions. It is still a challenge to fully understand these reasons and the process. The objective of climate niche based models is to define such a range of climate conditions rather than to model the process. The species may still grow well outside of its realized climate niche within its fundamental niche, but it may compromise it productivity, resilience, and its competitive advantages.

The relationship between the species distribution and climate variables is often complex. A multivariate linear or a nonlinear model is usually not able to accurately describe such a relationship. Thus, machine-learning approaches, Random Forest in particular, are widely applied in modelling climate niches of ecosystems or species. Although a Random Forest model is not explicitly interpretable, the importance value assigned to each climate variable allows us to rank the contribution of all climate variables. We identified the top 10 most important climate variables for each species, which can help us better understand the relationships between the species' distribution and climate variables. Some of the important climate variables are common among all the species, such as continentality (TD) and precipitation in summer months (PPT_JJA), while others are species specific (Table 3.1).

Random Forest has been widely used in climate niche modelling for its superiority in model accuracy and other favourable features. However, it requires a relatively balanced sample sizes between the classes of the dependent variable. For the presence and absence data in species climate niche modelling, the sample size of absence is usually much larger than that of the presence. Re-sampling is often applied to the absence data in order to keep the sample balanced between the two classes (Rehfeldt et al. 2006). On the other hand, the re-sampling may compromise the representation of the conditions for the absence in the model. The composite modelling approach applied in this study used the combined predictions generated through multiple models built with repeatedly and independently sampled absence data while the presence data remained the same. This approach satisfies both the requirements for a balanced dataset and a good representation of the absence conditions, thus improving the reliability of the climate niches for the species modelled in this study. The high consistency in predictions of the 10 repeated models indicates that the climate niches predicted through this approach are reliable.

3.4.2 Consensus projections for the future

Uncertainty in the future climate is probably the greatest challenge in assessing the impact of climate change on forest ecosystems and tree species, and therefore in developing adaptive strategies in forest resources management for the future. There are four greenhouse gas emission scenarios in the latest IPCC report, and over 20 general circulation models (GCMs). For a given period, there are over 80 (4 scenarios x 20 GCMs climate change scenarios) different projections of climate conditions. From a modeller's point of view, projections for a large number of climate change scenarios are resource demanding and time consuming, as the spatial datasets are usually huge. Therefore, most of the future projections involve only a small number of climate change scenarios. Some studies used ensembles by averaging over GCMs or emission scenarios. However, such ensembles may cancel out the spatial and seasonal patterns of specific GCMs as discussed in Wang et al. 2012.

From a practitioner's point of view, it is almost impossible to develop multiple adaptive options. In reality, if there are too many options, it might mean no option and no action will take place. Consensus projections aggregating multiple individual projections in a previous study (Wang et al 2012) provided an effective option for practical applications. In this study, we used the same approach to project the shift in geographic distributions of climate niches for each of the four forest tree species based on 12 climate change scenarios. We believe that the consensus projections provide a scientific basis for the assessment of climate change impacts on these species, and for the development of adaptive strategies in forest resources management under a changing climate. Specific characteristics of the consensus projections for each species are described below.

3.4.3 Chinese fir

Our results suggest that the geographic distribution of the climate niche for Chinese fir is projected to substantially contract. The contraction in its current distribution areas, particularly in the south, is not a surprise as the warmer climate conditions south of the current distribution are projected to move into the current distribution (Figure 3.2). What surprised us for this wide spread species is that it is not projected to considerably expand northward to new locations, as has been projected for most tree species in other studies.

The limited northward expansion is probably attributable to the spatial pattern of precipitation in China. The current species distribution and predicted current climate niche are within areas with mean annual precipitation (MAP) above 1000 mm (Figure 3.7). It is possible that this amount of MAP is required for this species to adapt. Under the future climates, the geographic distribution of temperature suitable for this species is projected to move northward. However, the geographic distribution of mean annual precipitation is not projected to move along with the temperature (Figure 3.7). The areas with MAP above 1000 mm are still mostly south of the Yangzi River. The sharp contrast in precipitation between northern and southern China appears to play an important role in the direction of future projections and may have limited the northward expansion of the climate niche for this species. However, it's worth mentioning again that the climate niche modelled in this study (or in the vast majority of other studies) is a realized climate niche. It depends on the climate conditions currently occupied by the species. Whether or not Chinese fir can grow outside of the current climate niche is unknown and need to be further explored through field experiments, such as provenance tests.

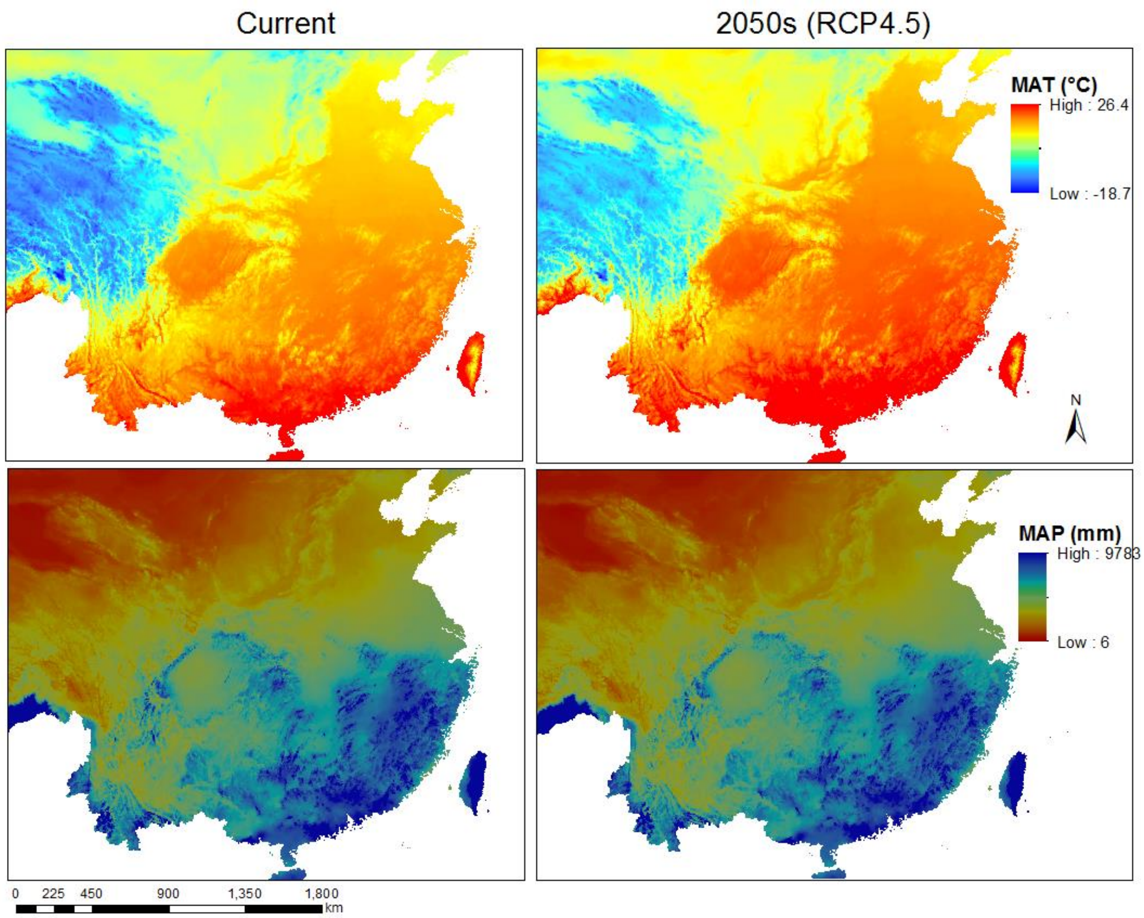

Figure 3.7. Distribution of mean annual precipitation (MAP) for 1961-1990 (left) and 2080s (right) projected by one of the AR5 GCM: HadGEM2.

The projected dramatic decline in the area suitable for Chinese fir is striking, as this species is one of the most important forest species in China in terms of both its economic values and ecosystem functions. In order to confirm our projections, we also modelled and projected the climate niche using a process- and niche-based hybrid model as described in Section 7.2 of Chapter 7. The projections of the hybrid model indicated some level of northward expansion, however, projected potential in productivity was extremely low. Thus, the results of the two modelling approaches are basically in agreement.

Our results would provide early warning for policy makers and practitioners to develop adaptive strategies in species selection and forest management practice in order to adapt to future climates. Otherwise, dramatic financial loses may occur, and ecosystem functions may be considerably compromised.

3.4.4 Masson pine

The climate niche of Masson pine overlaps almost entirely with that of Chinese fir, but it has a broader range in terms of both temperature and precipitation than Chinese fir (Table 3.2 and Figure 3.2 ~ 3.6). Projected contraction in the current distribution area for the climate niche of this species is much less (-17%) than that of the counterpart (-34%). However, these two species share the same feature – that is no substantial northward shift being projected in future climates.

The contraction of the climate niche is projected mostly to occur only in the trailing end of its current distribution in the south. This contrasts the projections for Chinese fir, for which the contraction is also expected to occur in the central distribution areas. This is probably attributable to the broader climate niche of this species; the current distribution extends far beyond that of Chinese fir, all the way down to the edge of the continent. Therefore, Masson pine may provide a good alternative to Chinese fir in species selection for reforestation and afforestation in the future climate.

3.4.5 Chinese pine

The consensus projections for Chinese pine falls into our normal expectation – contraction in the trailing edges and expansion in the leading ends. Instead of shifting northward, our projected climate niche for this species shifts mostly westward. This is not a surprise based on the topography in China, as there is higher elevation in the west. A dramatic increase in the elevation of the climate niche is projected for the future periods, with an expected increase of over 1100 meters by 2050s.

The total area of climate niche for this species is projected to increase substantially (about 50%). Chinese pine is a drought tolerate forest tree species with a relatively fast growth rate. Drought is projected to be a major future challenge in general according the IPCC Fifth report (IPCC, 2014). This is particularly true in northern and western China. This trend, together with our projected increase in areas suitable for Chinese pine, suggests that Chinese pine may play an important role in forestation in China in the future.

3.4.6 Douglas-fir

Douglas-fir is another species in this study with future projections following a typical northward and upward shift in the geographic distribution of its climate niche. Meanwhile, a substantial expansion in the climate niche area was projected. This is good news for forestry as this species is one of the most productive, and economically and ecologically important species. This trend is particularly favorable to British Columbia, Canada, where the expansion would mostly occur. Preparation for the selection of seed sources and for seed production should be seriously considered to take the advantage of this opportunity.

3.4.7 Blue Gum

For the species as a whole, the climate niche geographic distribution for Blue Gum is projected to shift southward towards cooler conditions. However, the shift is limited by the ocean at the leading edge, and resulted in a contraction in the total climate niche area for this species in the future periods (by 24% in 2050s, Table 3.2). The level of the contraction varies considerably among subspecies.

The most impacted subspecies include *E. glibulus* ssp. *pseudoglobulus* and *E. glibulus* ssp. *Bicostata*. The climate niches of these two subspecies are predicted to almost completely disappear and contract by 50% by 2050s, respectively (Table 3.3). This clearly indicates that climate change would bring in new challenges in maintaining the current level of biodiversity. In contrast, the total area of the climate niche for the major subspecies *E. glibulus* ssp. *globulus* is projected to have no change. Although some contraction is predicted to occur in the mainland, predicted expansion on the Tasmania Island would compensate for the loss.

3.5 Conclusions

Climate niches were modelled and mapped for five economically and ecologically important forest tree species in the Asia-Pacific at high accuracy. The maps of climate niche distributions, including areas both currently occupied and unoccupied but climatically suitable for the species, will be useful for afforestation and ecosystem restoration using these species. Important climate variables identified for each species may help us to better understand the relationships between species distribution and climate conditions. This study's use of consensus projections aggregating multiple individual projections that use multiple climate change scenarios provided a solid basis for the assessment of climate change impact on these species, and for the development of adaptive strategies in forest resources management under a changing climate, particularly in consideration of the uncertainty of future climate. We found that both the magnitude and the spatial patterns of climate change impact on the geographic distribution of climate niches varied among species depending on the regions and topography of the species distribution.

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Chapter 4 -- Pilot study and development of recommendations for SFM practices for adaptation

4.1 The application of FORECAST Climate to evaluate the long-term impacts of climate change on forest growth and development in the MKRF and Fujian Pilot sites.

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4.1.1 Introduction

Shifting patterns of climate associated with global climate change can have a significant impact on the long-term growth and development of forest ecosystems. Not only can such changes influence growth rates (e.g. Zhao and Running 2010), they can also lead to changes in forest water relationships and drought-induced mortality (Allen et al., 2010). It is essential that forest managers begin to account for the potential implications of such changes in the development of sustainable forest management strategies. Here we describe the application of a process-based model, FORECAST Climate (Seely et al., in press), to evaluate the potential impacts of alternative climate change scenarios on a coastal forest ecosystem type in British Columbia and a Chinese-fir plantation in Fujian Province, China.

4.1.2 Methods

FORECAST Climate was developed as an extension of the hybrid forest growth model FORECAST (Kimmins et al. 1999) created through the dynamic linkage of FORECAST with the stand-level hydrology model ForWaDy (Seely et al. 1997). The linked model is capable of representing the impact of climate and climate change on forest growth dynamics. Specifically, it includes detailed representations of the relationships between temperature and water stress on growth rates, as well as the effect of temperature and moisture contents on decomposition and nutrient cycling. The model also includes a function to represent mortality associated with severe drought events.

FORECAST Climate was calibrated for Douglas-fir (*Pseudotsuga menziesii*), western redcedar (*Thuja Plicata*), and western hemlock (*Tsuga occidentalis*) at the Malcom Knapp Research Forest (MKRF) located in coastal British Columbia, and for Chinese-fir (Lacelotta Cunninghamia) plantations in Fujian Province, China.

Development of Climate Change Scenarios

To explore the potential impacts of climate change on the growth and development of forests within the study areas, climate change projections were taken from different combinations of global circulation models (GCMs) included as part of the Intergovernmental Panel on Climate Change AR5 analysis and emission scenarios. In the case of the MKRF the two models included the HadGem2 and

CanESM2 models. The climate scenarios utilized for the Fujian pilot project are shown in comparison to the reference climate data in Figure 4.1.

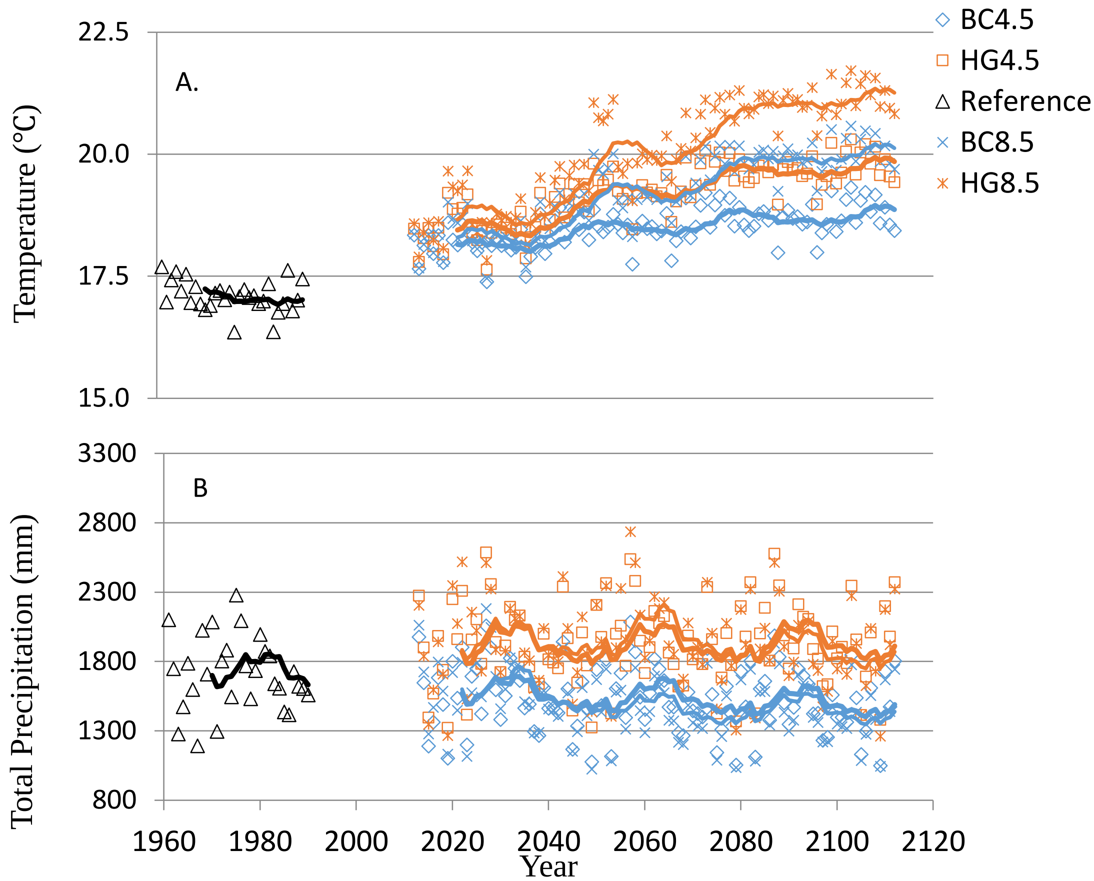

Figure 4.1 Historical reference climate data and projected pattern of change for A) mean daily air temperature, and B) total precipitation for the next 100 years for the Fujian Pilot study area based on four downscaled climate change projections. Lines represent the 10-year moving average for each series. HG refers to the HadGem2 model and BC refers to the Beijing Climate Centre Climate System and the numbers 4.5 and 8.5 refer to specific emission scenarios.

Application of FORECAST Climate to the Pilot area

FORECAST Climate was calibrated for major tree species in each of the study areas using data derived from various literature sources. These data include species-specific growth responses to daily temperature and moisture availability. Data describing vulnerability to drought-related mortality were also provided. Lastly, the model was applied to simulate a series of representative forest types (analysis units) found within each of the study areas. These forest types vary in terms of underlying soil fertility as well as variations in species combinations or stand management practices. Details are provided in

Appendix 4.1. The calibrated model was used to simulate the long-term growth and development of the different analysis units.

4.1.3 Results / Discussion

The model predicted an increase in productivity of 50-70% for Douglas-fir and 25-34% for western hemlock stands after 60 years of climate change (year 2073) relative to the reference climate scenario (Fig. 4.2). This was primarily related to an increase in the length of the growing season and an associated increase in nutrient cycling rates. While the climate change simulations also showed a significant increase in drought-related mortality, the increase in site productivity more than offset the losses due to mortality.

Climate change was projected to have a smaller positive impact on the productivity of Chinese-fir plantations (5-7% over the reference climate) in the subtropical Fujian study area. Again, the increase in productivity was related to an increase in the length of the growing season. A sensitivity analysis was conducted to determine whether the results of the Fujian simulations would deviate significantly if the sensitivity of Chinese fir to elevated temperature was increased at mean daily temperatures above 20° C. We also examined the effects of increasing the sensitivity of Chinese fir to moisture stress. In both cases, the changes in parameters led to only small changes in the model output suggesting the model results are robust for the Fujian area.

It is important to note that the increases in productivity projected by the model as a result of climate change may not be realized if the change in climate regime also leads to an increase in the activity of biotic and abiotic disturbance agents. Further work is required to explore the potential of such events. The calibrated FORECAST Climate model may be used to exam additional climate change scenarios as well as different management alternatives designed to improve adaptation.

The detailed report for the Fujian and MKRF applications are attached as Appendix 4.1 and Appendix 4.2, respectively.

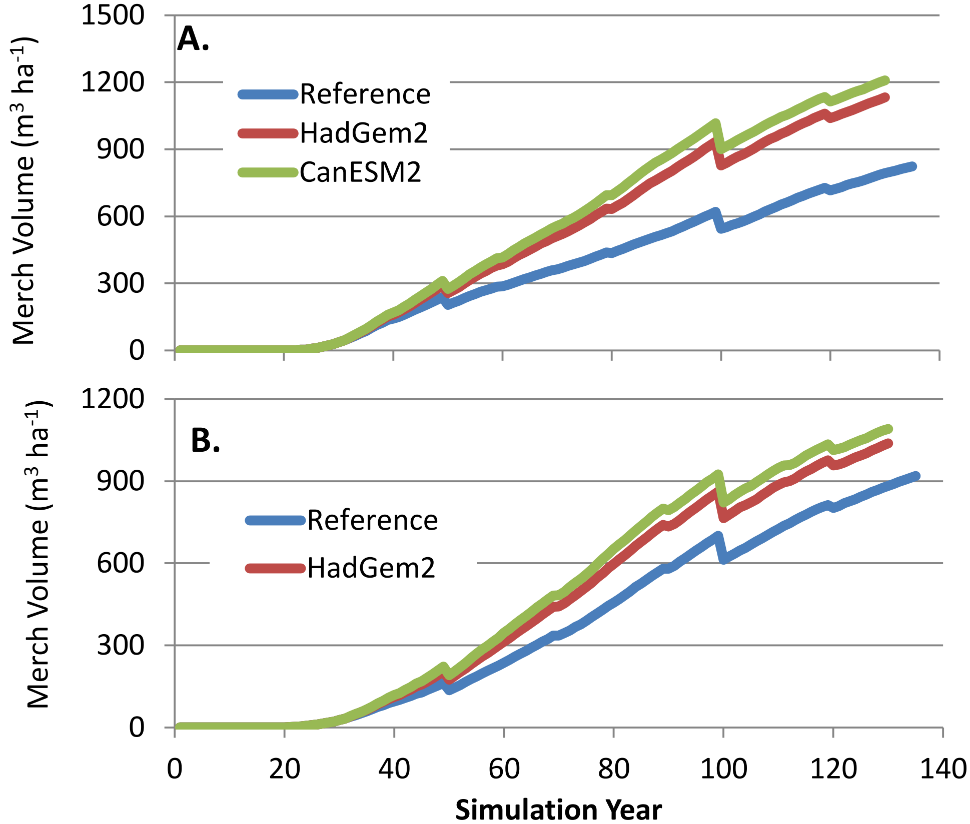

Figure 4.2. Simulation results from the MKRF pilot site showing the relative impact of 2 climate change scenarios on the long-term production of merchantable volume for A) Douglas-fir and B) western hemlock relative to the reference climate scenario.

4.1.4 Recommendations

Fujian Chinese Fir

- More research is required to explore potential implications of increased variability in precipitation on Chinese-fir growth.
- More research is needed to assess the potential for climate change to influence the activity of abiotic and biotic disturbance agents associated with Chinese-fir
- Chinese-fir will remain a viable and productive plantation species in the Fujian region. However, climate conditions in the region will become more favorable to other more tropical species as suggested by the changes in the realized niche area for Chinese fir (see Section 3).

- The inclusion of other species such as Masson pine and hardwoods will lessen the risk of catastrophic failure of fir plantations due to disturbance.
- FORECAST Climate represents a useful tool for the evaluation of future climate impacts on forest growth and development

MKRF

- Climate change is expected to improve the productivity of the key conifer species in the region with the benefits being the greatest for Douglas-fir followed by western redcedar and western hemlock
- The model projects that there will be an increase in growing season moisture stress and that this could lead to increased drought-related mortality particularly in western hemlock.
- More research is required to explore potential implications of increased variability in precipitation on conifer mortality
- More research is needed to assess the potential for climate change to influence the activity of abiotic and biotic disturbance agents

4.1.5 Literature Cited

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4.2 Evaluating management trade-offs between economic fiber production and ecosystem services in the context of climate change in a Chinese-fir dominated forest plantation in Fujian Province.

By Haijun Kang and Brad Seely, Department of Forest Resources Management,

University of British Columbia

4.2.1 Introduction

Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook.), an evergreen conifer species, is one of the most important commercial species in China. It is a valuable timber species with qualities that render it useful for construction and furniture manufacturing (Huang 2013; Zhang et al. 2013). In addition to its importance as a source of fiber, Chinese fir plantations also play an important role in the provision of forest ecosystem services including water and soil conservation, climate regulation, pollutant absorption, etc. (Tian et al. 2002; Wang et al. 2009). Forest management decisions can have a wide range of impacts on both the production of fiber for economic gain, and on the long-term flow of ecosystem services from forest resources. In some cases, management decisions made with the goal of improving the flow of economic resources will have negative impacts on other important ecosystem services including biodiversity and carbon sequestration. Such management trade-offs can become particularly complex when accounting for the potential impacts of climate change for forest health, growth, and development.

In this study, we examined the trade-offs associated with different forest management strategies in the context of a changing climate. Specifically, we employed the stand-level FORECAST Climate model in conjunction with a landscape-scale model to project the impact of alternative management scenarios on the flow of both economic wood fiber and specific ecosystem services under different climate change scenarios within a Chinese fir-dominated forest plantation located in Shunchang County, Fujian Province.

4.2.2 Methods

Trade-off Analysis

A landscape-level analysis of the trade-offs between economic production and ecosystem services was conducted for a series of alternative management scenarios using output from FORECAST Climate model in conjunction with a landscape-scale model. To facilitate the landscape-scale analysis, the study area was divided into discrete analysis units. A description of the development of specific analysis units for the study area is provided in the detailed project report submitted towards the completion of the larger APFNet project.

The Landscape Summary Tool (LST) and Indicators of Ecosystem Services

A Landscape Summary Tool was designed in Microsoft Excel to facilitate the calculation of indicators of ecosystem services. It works by dividing the whole project area into discrete analysis units and projecting the development of indicators in those units. The simulated age of each polygon within the landscape is used to model specific stand-level data, and is linked to a specific analysis unit. The nature of the linkage between FORECAST Climate and the LST model is shown in Figure 4.3.

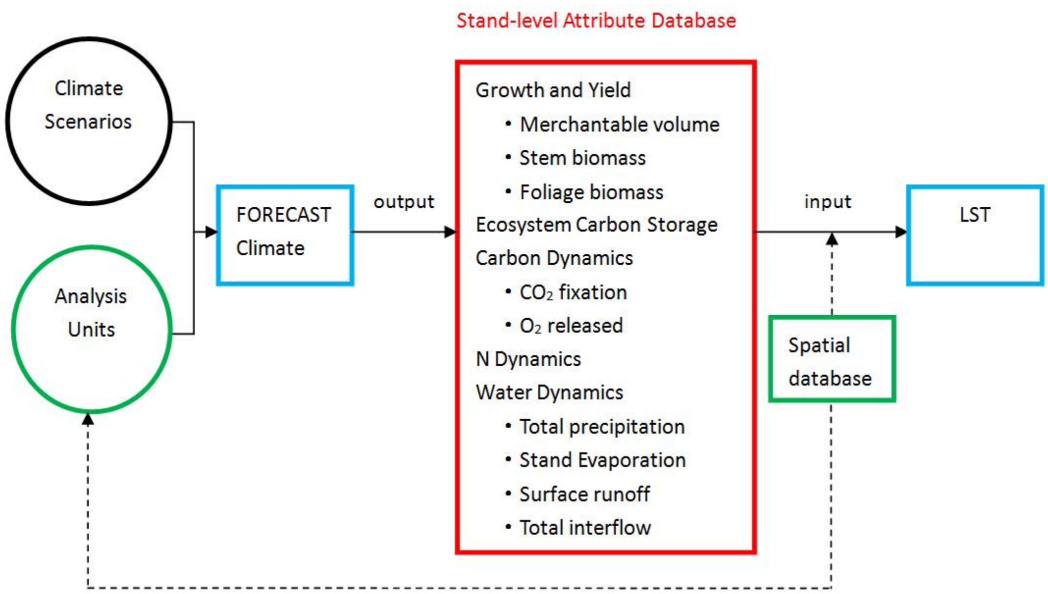

Figure 4.3. A schematic diagram illustrating the relationships and data transfer pathways between the FORECAST Climate and LST models.

The stand attribute database derived from FORCAST Climate was used to calculate values for specific indicators for the trade-off analysis. In this study, we used a series of metrics defined in a published Chinese report entitled "Specification for assessment of forest ecosystem services in China" (LY/T 1721-2008) to evaluate the flow of ecosystem services from the study area. In total we selected 9 indicators, 2 for economic production (volume harvested and biomass harvested), and another 7 for non-economic services (see Appendix 4.1).

Development of alternative management scenarios

Twenty-seven alternative management scenarios were developed using a factorial analysis approach (3 rotation length scenarios * 3 harvest retention options * 3 climate scenarios) (Figure 4.4). Employing the LST model, all 27 alternative management scenarios were explored over a 50-year time horizon. The absolute output values calculated for each of the indicators were converted to relative values (scaled from 0 to 1) to facilitate direct comparisons among indicators. We included a variable weighting decision approach to allow the users to determine the importance of each indicator. Through this, a total score based on the weighted sum of the indicators is calculated for each scenario to allow for a ranking of management options. Finally, a decision matrix output table was produced to illustrate the trade-off analysis results.

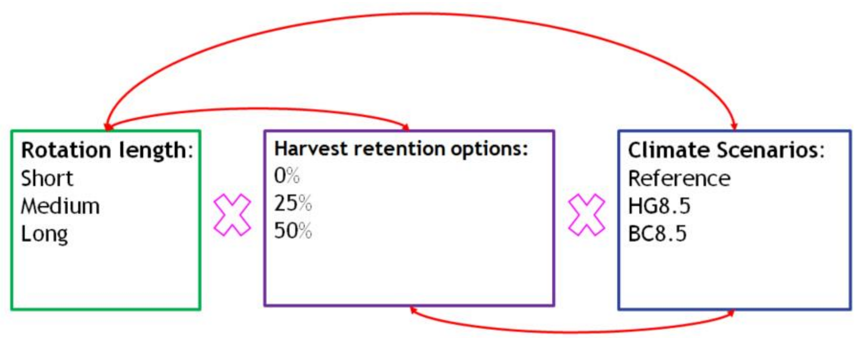

Figure 4.4. Combinations of rotation length, harvest retention and climate scenarios.

4.2.3 Results/Discussion

An example of the development of individual indicators of ecosystem services at the stand level is shown for two analysis units under reference climate (Figure 4.5).

Merchantable volume, stem biomass, total ecosystem carbon storage, N content, and pollutant absorption generally increased with stand age, while the rates of carbon fixation and oxygen released tended to decline with increasing age. Analysis unit 105 (Figure 4.5 A,B), with an objective of large diameter log production, included several thinning events which had a negative impact on the development of some indicators relative to the equivalent ‘ecological forest’ analysis unit (AU 108, Figure 4.5 C,D). The results show that stem biomass consistently accumulates more quickly than merchantable volume. Thus, the use of longer rotation lengths provides greater production of merchantable volume at the landscape-scale.

An example of the indicator output matrix generated by the LST for the study area landscape tradeoffs analysis is shown in Table 4.1. A total of nine indicators were calculated for each alternative management scenario and used to calculate a score based on the weighting factors assigned in the top row. We developed the LST as a decision-support tool for forest managers, as the output matrix allows the users to decide which management option is the best according to their determination of the importance for each indicator. The combination of weighting factors selected in the decision matrix shown in Table 4.1 resulted in the long rotation with no retention management combination being selected as highest-ranking scenario regardless of the future climate regime.

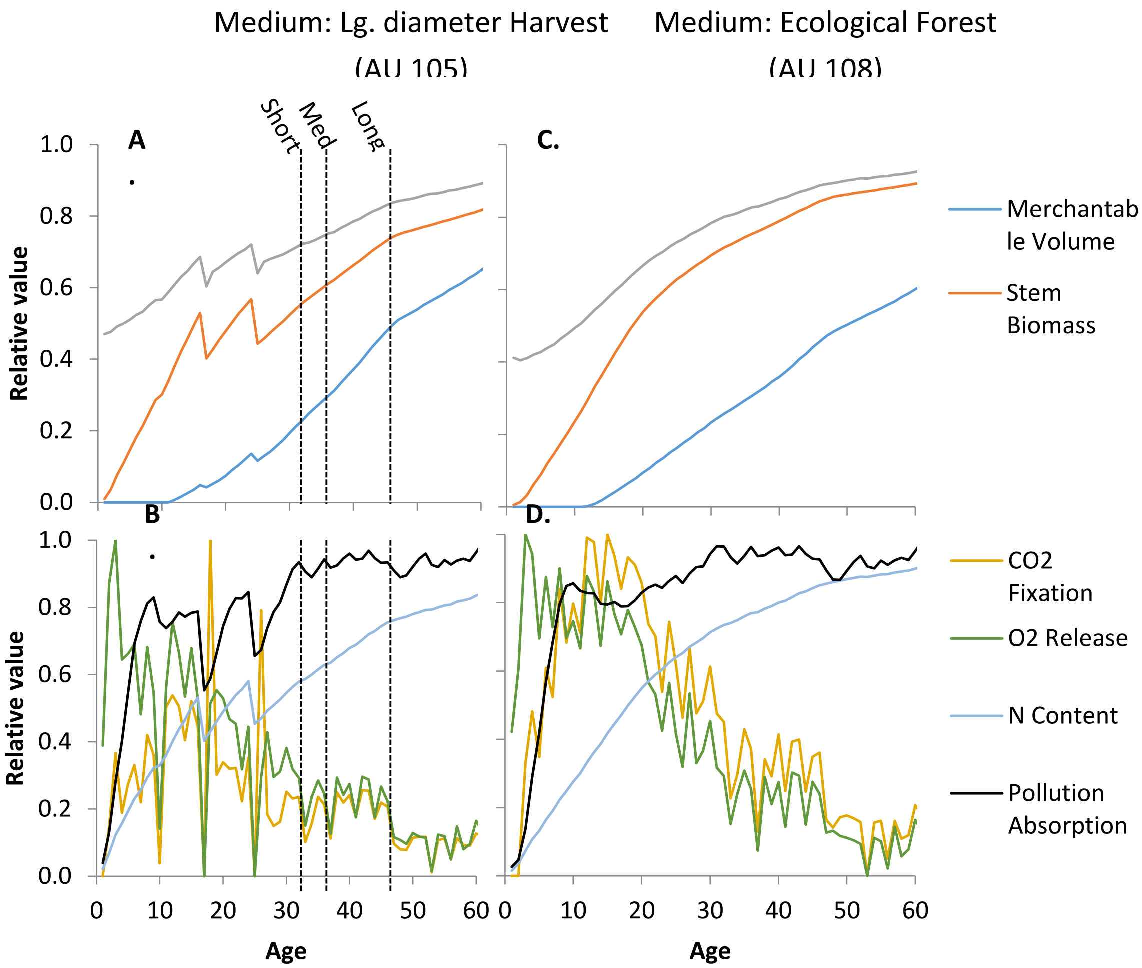

Figure 4.5. An example of the development of indicators at the stand-level for two different analysis units. Panels A & B show output for the medium site quality where the plantation is managed to produce large-diameter timber (AU 105). The dashed lines show the different rotation lengths used for this analysis unit in the landscape management scenarios (see Appendix 4.1). Panels C & D show output for the medium site ecological forest unit (no harvesting or thinning). Output for merchantable volume, stem biomass and ecosystem C storage are shown in panels A&C, while panels B & D show output for CO_2 fixation, O_2 release, biomass N content and pollution absorption potential.

Table 4.1. Output from the LST model in the form of an indicator matrix with example weighting factors provided for each indicator. Nine scenarios with different retention levels and rotation lengths are grouped within each of the three different climate scenarios. The color scale ranges from green representing the highest-ranking scenario to red, representing the lowest ranking scenario.

Weight (0-1)			0.5	0.5	0.7	1	1	0.5	1	1	0		
Scenario													
Rotation Length	Retention	Climate	Vol_ Harv	Bio_ Harv	Eco_ C	CO2_ Fix	O2_ Rel	N_ cont	Pol_ Abs	Soil_ Fert	Water _Reg	Rank	Score
short	0%	Ref	0.64	0.93	0.83	0.91	0.92	0.72	0.73	0.52	0.81	5	4.79
short	25%	Ref	0.48	0.69	0.88	0.84	0.82	0.79	0.77	0.70	0.80	7	4.73
short	50%	Ref	0.32	0.46	0.92	0.78	0.72	0.87	0.81	0.88	0.80	9	4.66
med	0%	Ref	0.75	0.86	0.85	0.91	0.88	0.75	0.76	0.59	0.80	2	4.92
med	25%	Ref	0.57	0.65	0.89	0.84	0.79	0.82	0.79	0.76	0.80	4	4.82
med	50%	Ref	0.38	0.43	0.94	0.78	0.70	0.89	0.82	0.92	0.79	8	4.72
long	0%	Ref	0.83	0.71	0.89	0.87	0.79	0.82	0.80	0.75	0.79	1	5.01
long	25%	Ref	0.62	0.53	0.92	0.82	0.72	0.87	0.82	0.88	0.79	3	4.89
long	50%	Ref	0.41	0.35	0.96	0.76	0.65	0.92	0.84	1.00	0.79	6	4.77
short	0%	HG8.5	0.79	1.00	0.86	1.00	1.00	0.77	0.84	0.46	1.00	6	5.18
short	25%	HG8.5	0.59	0.75	0.91	0.93	0.90	0.86	0.90	0.65	1.00	8	5.12
short	50%	HG8.5	0.40	0.50	0.97	0.86	0.79	0.94	0.96	0.85	1.00	9	5.06
med	0%	HG8.5	0.93	0.94	0.88	1.00	0.96	0.82	0.88	0.54	1.00	2	5.33
med	25%	HG8.5	0.70	0.70	0.93	0.93	0.87	0.89	0.92	0.72	1.00	4	5.23
med	50%	HG8.5	0.46	0.47	0.98	0.86	0.77	0.96	0.97	0.89	1.00	7	5.13
long	0%	HG8.5	1.00	0.77	0.93	0.96	0.87	0.89	0.93	0.71	0.99	1	5.44
long	25%	HG8.5	0.74	0.57	0.96	0.90	0.80	0.94	0.96	0.85	0.99	3	5.31
long	50%	HG8.5	0.50	0.38	1.00	0.84	0.73	1.00	1.00	0.98	1.00	5	5.19
short	0%	BC8.5	0.74	0.98	0.85	0.97	0.98	0.76	0.80	0.47	0.70	5	5.06
short	25%	BC8.5	0.55	0.73	0.90	0.91	0.88	0.84	0.85	0.67	0.68	8	4.99
short	50%	BC8.5	0.37	0.49	0.95	0.84	0.78	0.92	0.90	0.86	0.66	9	4.93
med	0%	BC8.5	0.86	0.91	0.87	0.98	0.94	0.80	0.83	0.56	0.69	2	5.20
med	25%	BC8.5	0.65	0.69	0.92	0.91	0.85	0.87	0.87	0.73	0.67	4	5.10
med	50%	BC8.5	0.43	0.46	0.96	0.84	0.76	0.94	0.91	0.90	0.65	7	5.00
long	0%	BC8.5	0.94	0.75	0.91	0.93	0.85	0.87	0.88	0.72	0.66	1	5.30
long	25%	BC8.5	0.70	0.56	0.95	0.88	0.78	0.92	0.91	0.86	0.65	3	5.17
long	50%	BC8.5	0.47	0.37	0.98	0.82	0.71	0.98	0.94	0.99	0.64	6	5.05

4.2.4 Conclusions

- A decision matrix was implemented to allow users to weigh the relative value of specific indicators as part of the decision making process.
- The tool allows for an efficient evaluation of the tradeoffs between management designed to optimize economic return versus that designed to maximize the flow of non-commercial ecosystem values from Chinese-fir forests.

4.2.5 Literature Cited

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4.3 Multi-value trade-off framework for decision making in a changing climate in the MKRF pilot study area in BC, Canada

By QingLin Li, Forest Analysis and Inventory, BC Ministry of Forestry, Canada

4.3.1 Introduction

Management objectives on forest stewardships, especially on public lands, have broadened from a traditional focus on timber supply to include broader categories of ecosystem goods and services. Much of this paradigm shift in North America and other regions of the world are due mainly to interests in conserving biodiversity, combating climate change, and respecting aboriginal culture and rights. Recent concerns about climate change have extended management objectives further to include carbon storage for the abatement of increases in atmospheric CO_2. Such changes are particularly relevant in areas where easement and subsides for carbon storage may provide important economic incentives, such as reducing emissions from deforestation and forest degradation (REDD) and forest carbon offset projects. Management practices related to timber production may also have an impact on carbon storage and other values that ecosystems provide. Thus, it is critical for managers and practitioners to understand the potential trade-offs and/or synergies associated with a broad suite of goals that sustainable forest management attempts to achieve.

As a consequence, managers and decision makers need straightforward methods to quantify the individual or combined benefits and trade-offs of multiple, potentially conflicting objectives. In cases where some objectives are considered more valuable than others, individual objectives can be weighted to incorporate differences into an overall calculation and trade-off. The linear and/or non-linear trade-off functions can also be added into an optimization function to achieve an overall (sub)-optimal management solution over a long period of time.

The overall objective of this pilot study was to develop a conceptual framework for strategic planning using a meta-heuristic method to explore and understand trade-offs among multiple values, and potentially apply this framework in other Asia-Pacific economies. In particular, the framework is able to assess the impacts of different forest management regimes on ecosystem values, evaluate management alternatives' influences on these values and their trade-offs/synergies, and address some of the complexities associated with the effects of climate change on ecosystems and decision making processes.

4.3.2 Methods

We designed a conceptual framework based on Li, et al (in review) suitable to our BC pilot study (Figure 4.6). This framework has the spatially explicit capability and complexity for advanced users who have very detailed inventory and management information, and also has the flexibility and simplicity for users who have less complex information to make strategic planning decisions.

This framework involves the following steps: (1) evaluate existing information, such as the kind of forest inventory data you have, the growth and yield information available for your forests, and determine if there are legal requirements within the forest (fish and wildlife habitats, endangered species habitats, visual quality requirement for tourism, etc); (2) determine values or group of values being considered in the analysis, such as timber volume and value, carbon storage, and/or revenue, etc.; (3) define management/planning alternatives that can be expressed by grouping these values into broader categories, such as environmental values that focus on different habitats, and economic values that can be addressed by timber volume and revenue. Each value can be assigned different weights and associated risk classes to assist decision-making; (4) conduct a trade-off analysis to further explore the alternatives and their relative importance in addressing the management goals; (5) communicate the results (Figure 4.6).

Ecosystem Carbon Analysis

The inventory-based forest ecosystem carbon budget model (CBM-CFS3) was employed to evaluate ecosystem carbon storage within the Pitt River watershed area (which encompasses the Malcolm Knapp study area) for the current climate scenario. Ecosystem carbon budgets (i.e. total ecosystem carbon storage and net ecosystem carbon balance) represent a key indicator for sustainable forest management. Projections of carbon density for different time periods under the reference climate were calculated for the study area. A detailed report of the methods employed and the results of this analysis to date are provided in Appendix 4.3.

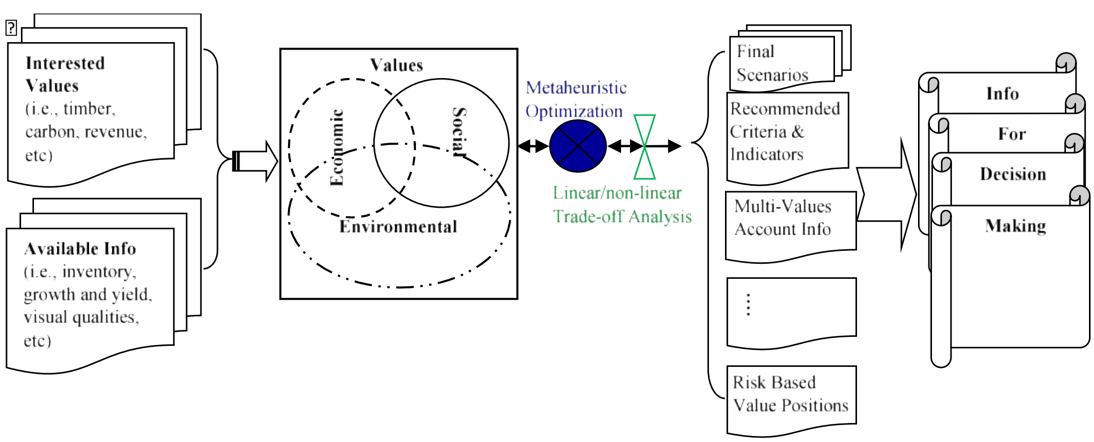


Figure 4.6. A conceptual flow diagram of a multiple value trade-off framework for decision support.

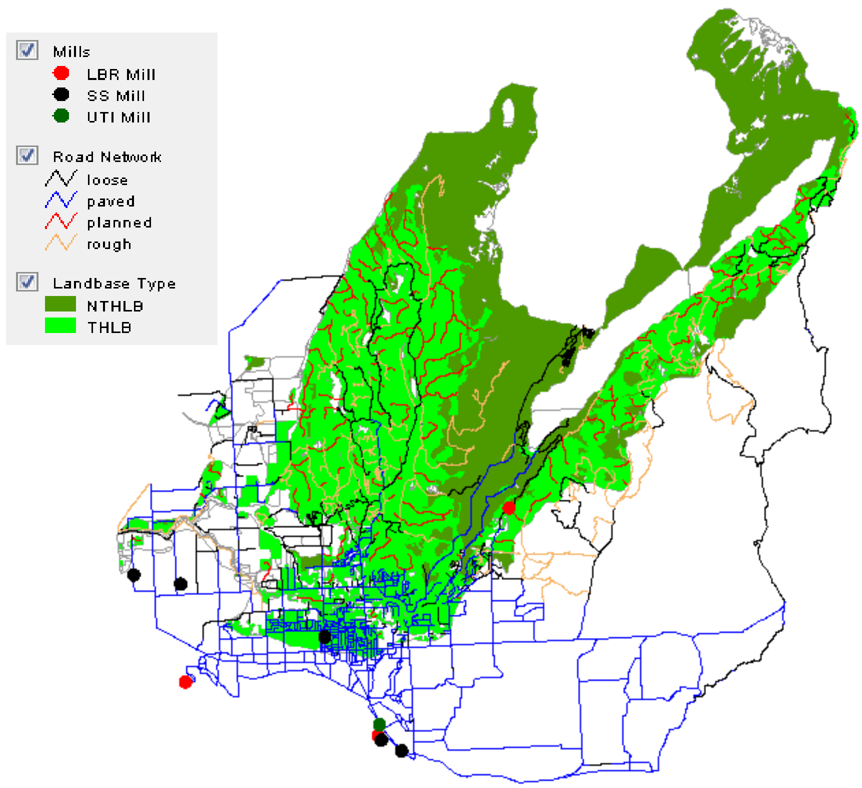


Figure 4.7. The Pitt River pilot study area in BC Canada. (LBR: lumber processing mill; SS: shakes and shingles; UTI: utility pole mill; NTHLB: non-timber-harvesting landbase; THLB: timber-harvesting landbase).

This framework was tested in the coastal region of British Columbia Canada (Figure 4.7). In this pilot study, we put our efforts on the framework development, mimicking the current management practice, and climate change impacts on the ecosystem and society (social impacts, Table 4.2).

Table 4.2. Indicators and their relative importance for different scenarios

	Initial		*Scenarios*		
Indicators	*Values*	*Unit*	*Current*	*RCP4.5*	*Mill Availability*
Harvest volume	1.53×10^4	M^3	High	Moderate	Moderate
NEP	1.00×10^4	Tonnes	None	Moderate	Moderate
HWP	n/a	Tonnes	None	Low	Low
Wildlife	2.34×10^2	Ha	High	None	None
Visuals	3.05×10^2	Ha	High	None	None
Green-up	1.24×10^2	Ha	High	None	None
Mills availability	n/a	M^3	100%	100%	60%

Note: RCP4.5-Representative concentration pathway 4.5 (IPCC AR 5 report); NEP-Net Ecosystem Productivity; HWP-Harvested Wood Products.

In this pilot site project, we defined three management scenarios: (1) the current management practices, which were defined as meeting the current social needs and legal requirements. For example, current resource management should provide cultural and spiritual areas for local and aboriginal communities. As for the legal requirements, government regulations require that public lands meet multiple use objectives, that they maintain certain areas of old growth forests for wildlife habitats, and that harvesting/management should not impact tourism, thus, visual quality should be maintained; also harvesting can only happen when the adjacent previously harvested area has been regenerated, and the trees meet certain height requirements to maintain ecological functions such as water holding capacity. (2) The climate change scenario Representative Concentration Pathway 4.5 (RCP4.5) was selected, because it is a mid-level emission scenario (higher than 2.6, but lower than 8.5), and more realistic to reflect climate change impacts on the BC coastal region. Also, the climate change model-CanESM2.0 was used to simulate future climate for our pilot area (Figure 4.8). (3) Mills availability scenario was selected based on the fact that climate change may cause significant damage to the BC coastal region's infrastructure. In order to simulate these potential impacts, we designed this scenario by using a spatially explicit modelling concept by adding road networks and saw mills spatial location to control the timber flow (Figure 4.7). In this scenario, we assume that the natural disturbance events such as wildfires and flooding reduce the mills to 60% of their full capacity; thus, the upstream harvesting will be impacted by the demand. Although there is potential diversion of log exports or longer transportation to other mills, we simply treated it as if these events would not happen to establish the worst-case scenario.

Climate change has the potential to accelerate temperate-maritime forest regrowth, while the magnitude of this synergistic response is species and stand age specific. We used FORECAST-Climate model to simulate species and stand age responses to climate change under RCP4.5 scenario (see Section 4.1)

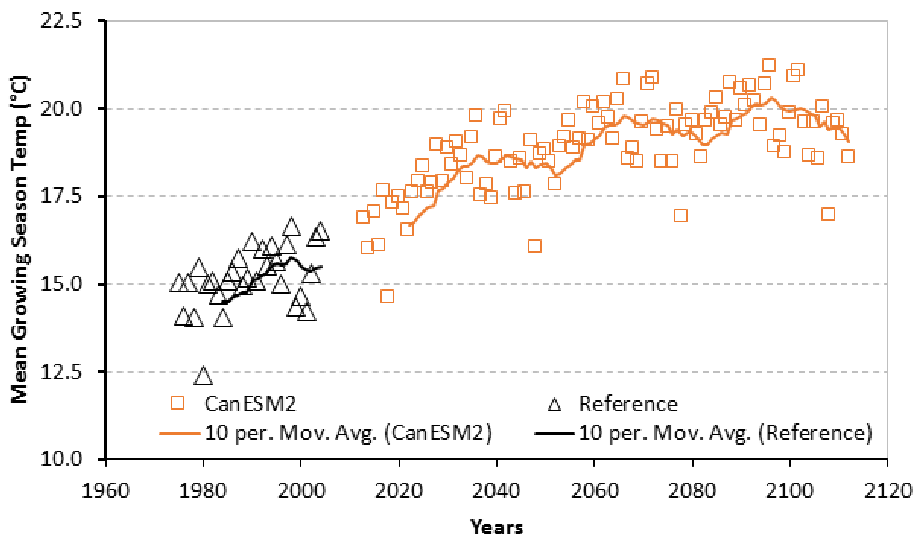
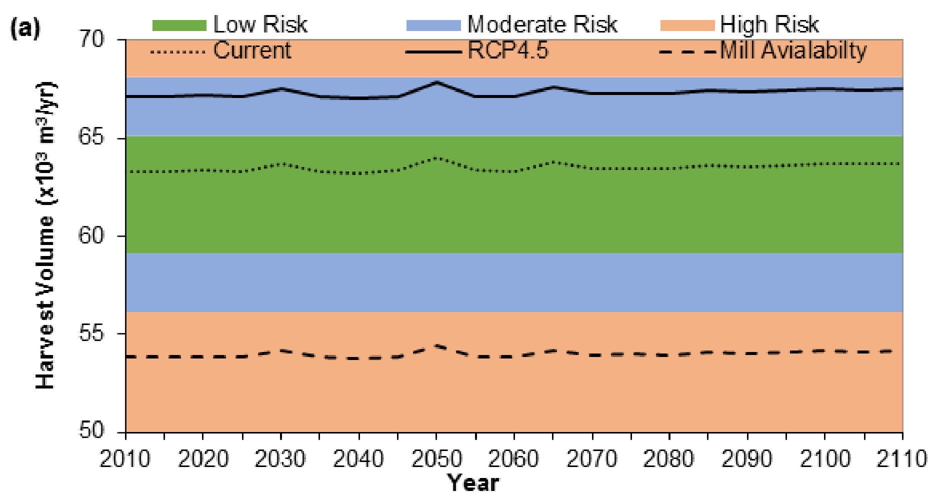


Figure 4.8. Project change in Mean growing season temperature for the RCP 4.5 emissions scenario using the CanESM2 model.

4.3.3 Results/Discussion

Risk is the combination of the probability of an event and its consequences; thus, it refers to cases for which the probability of outcomes can be ascertained through well-established theories with reliable complete data (IPCCC, 2004). A risk analysis then, is a probabilistic approach that quantifies the negative consequences of a hazard by multiplying its likelihood by the levels of susceptibility and value. Risk analyses are supported by probability theories, such as Kolmogorov probability theory, Bayesian probability theory, and fuzzy set theory. A common approach in practice is risk classes, which are defined at a broader context for strategic decision-making. For example, the timber volume to be harvested was determined through a complex timber supply review process, which considered all the potential impacts of timber harvesting on the ecosystem, environment, and society. If the harvesting is too low, the society (i.e., jobs) may be influenced, while if the harvesting is too high, the ecosystem sustainable yields may be impacted. Thus, as a rule of thumb, it is considered to be low or no risk, if the harvest level is within ±5% of normal harvest, moderate risk between ±5% to ± 10%, and high risk beyond ±10% (Figure 4.9 a). In contrast, for the net ecosystem productivity (NEP), an indicator proposed by Canadian Council of Forest Ministers for measuring ecosystem productivity, risk classes are defined by their statistics, such as standard deviation. If the NEP is ±1sd, it is low or no risk to ecosystems, with moderate risk between ±1sd and ±2sd, and high risk beyond ±2sd (Figure 4.9 b). All the indicators are assigned risk classes either based on practice or probability theory, which can be presented intuitively through figures and graphs (Figure 4.9).



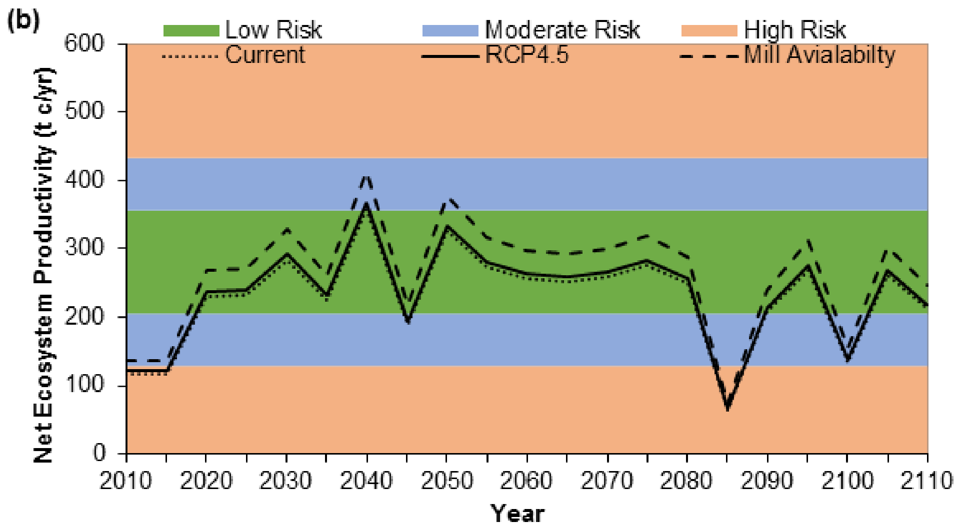


Figure 4.9. Simulated indicator values and their associated risk classes for each scenario (current management, RCP4.5 climate change, and climate change with limited mill availability) for the next 100 years in the MKRF pilot site. (a) timber harvest volume (m3/yr) and (b) net ecosystem productivity (tC/yr)

The temperature increase (i.e., RCP4.5) can accelerate temperate-maritime timber supply, while the limited mill availability due to climate change (RCP4.5) significantly reduced timber flow out of the ecosystem (Figure 4.9 a). However, the net ecosystem productivity does not change much in either scenario due to the harvests always targeting older stands, which commonly have lower growth rates (Figure 4.9 b). In this modelling framework, the sustainable timber supply from the current management practice scenario is achieved by maintaining high quality wildlife habitats, green-up, and visual quality conditions. During the analysis, the model used non-linear trade-offs among all the indicators while optimizing the timber flow. In contrast, the RCP4.5 scenario achieved a higher harvest level, which is achieved not only by higher yields, but also by trading green-up and visual quality conditions, although the violation is not significant (less than 3%). The RCP4.5 with limited mill accessibility reveals that a significantly lower harvest level over the analysis horizon was obtained, without violation of any constrains, but gaining very low ecosystem productivity (i.e., NEP) due to the pilot study site being dominated by mature and old growth forests. Thus, trading one ecosystem value for another/others is a system decision, and more often than not, the trade-off is not linear.

The risks associated with the trade-offs between the two comparative scenarios indicates that direct climatic forcing can cause an ecosystem response, but within the range of ecosystem recovery capability (or resilience) with almost no threats to the society. However, the indirect influence, such as mill accessibility dropping, can induce high-level threats to community livelihood, while the net gain to ecosystems (i.e., NEP) is not significant. Furthermore, as the harvest level decreases, more forests grow older, making them more susceptible to natural disturbances (i.e., insects and diseases).

4.3.4 Conclusions

In summary, the multi-value trade-off analysis framework offers a suitable planning and decision-making tool for forest resource management. It can provide a convenient platform to effectively accommodate the inherent complexity of resource management objectives, embracing ecological, biophysical, environmental, and social components, and capturing the multitude of concerns, issues, and objectives of stakeholders. In addition, forest management is dynamic and the objectives are evolving towards a sustainable and adaptive management paradigm, therefore, a significant gain can be made if this innovative framework represents different management objectives through its value system/indicator selections. Currently, there is a greater acceptance of multi-value modelling approaches to address stakeholders' interests around North America compared to other regions, however this framework can play a critical role in other economies in many practical aspects. In practice, a multi-value framework is better at meeting the many challenges faced by today's forest management. These challenges include providing decision support for multiple management objectives; participatory planning, especially in dealing with First Nations consultation, managing risks and uncertainty in a changing climate; trade-off and synergies of selecting one objective verse another; and making comprehensive use of different kinds of information from various sources. It is evident that the multi-value trade-off framework has great potential applications in forest management and land-use planning, and will increase in the future.

4.4 Australia Case Study

By Craig Nitschke, Dept. Forest and Ecosystem Science, University of Melbourne

4.4.1 Introduction

Eucalypt trees are important species to monitor under climate change. As a dominant genus in most habitats (Hughes *et al*., 1996), eucalypt response to climate change will have huge impacts on the Australian ecology. Additionally, eucalypts play an important role in protecting water catchments and are commercially valuable sources for timber and pulp wood. The climate scenario projections by the Intergovernmental Panel on Climate Change (IPCC) for Australia predict considerable shifts in climate variables, with increases in mean annual temperatures shifting from 0.4 to 1.2 °C by the 2020s and 1 to 4.6 °C by the 2080s, with a - 1 to - 41 % change in annual precipitation (Suppiah *et al.*, 2007). This predicted climate change is expected to have a significant impact on SE Australia's forest ecosystems due to the relatively narrow climatic range of the many of the region's tree species (Hughes *et al.*, 1996). Consequently, understanding how these forests will be affected by climate change and how vulnerable these species are will be essential to preventing economic and ecological loss.

4.4.2 Study Area

The description of the study area follows Mok et al. (2012). The Central Highlands Region (CHR) in Victoria, Australia contains approximately 2 million hectares of land under various management tenures: State forests comprise 25.6% of the study area; national parks and reserves: 9.7 %; forest plantations: 0.4 %; and private land is 61 %. In the CHR, elevation ranges from 75 to 1600 m above sea level, with lower elevation near the edges of the region and higher elevation at Mount Baw Baw region in the southeast and Lake Mountain plateau in the north. Annual rainfall ranges between 600-2000 mm, and mean annual temperature ranges between 5.4 °C and 14.2 °C. The region has ten major ecosystems, which are primarily dominated by eucalypts (*Eucalyptus* spp.) (Fig. 1): (1) Heathy Dry Forest, (2) Shrubby Dry Forest, (3) Lowland Forest, (4) Herb Rich Foothill, (5) Damp Forest, (6) Wet Forest, (7) Montane Wet Forest, (8) Montane Damp Forest, (9) Cool Temperate Rainforest, and (10) Subalpine Woodland (ecosystem descriptions based on Department of Natural Resources and Environment, 1998). The Dry Forest Complex, ecosystems 1 to 4, occurs from sea level up to 900 m on warm and dry sites. This ecosystem grouping is characterised by seven variants and dominated by many species. Messmate Stringybark (*E. obliqua*) is one of the dominating species in the foothill variants transitional between dry and damp forest. The Dry Forest species are typically drought tolerant and have high vegetative reproductive ability (via sprouting). Damp Forest occurs from 200 to 1000m in elevation on warm, moist sites, and local abundances of Mountain Ash (*E. regnans*) occur. Wet Forest is dominated by Mountain Ash, and is located in areas with cool climatic conditions and high rainfall at elevations that range from 500 to 900 m. Montane Wet Forest is dominated by Alpine Ash (*E. delegatensis*) which grows in pure or mixed stands with Shining gum (*E. nitens*). This ecosystem typically occurs from 900 to 1200 m in area areas of high rainfall and colder climatic conditions than occur in areas dominated by Wet Forest. Both Wet and Montane Wet Forests are dominated by species that rely predominantly on seed-based regeneration. Montane Damp Forest occurs in damp, cool areas between 800 and 1000m and Messmate Stringybark is among the dominating species; at higher elevations Alpine Ash dominates. Cool Temperate Rainforest occurs from 200 to 1200m and develops in cool, wet areas, primarily gullies and riparian areas, which have not had a significant fire event for 200-300 years. Subalpine Woodland typically occurs at elevations above 1100 m and is dominated by Snow Gum (*E. pauciflora*) with local occurrences of Wet Montane Forest species occurring upwards to 1400 m. The study area is illustrated in Figure 4.10.

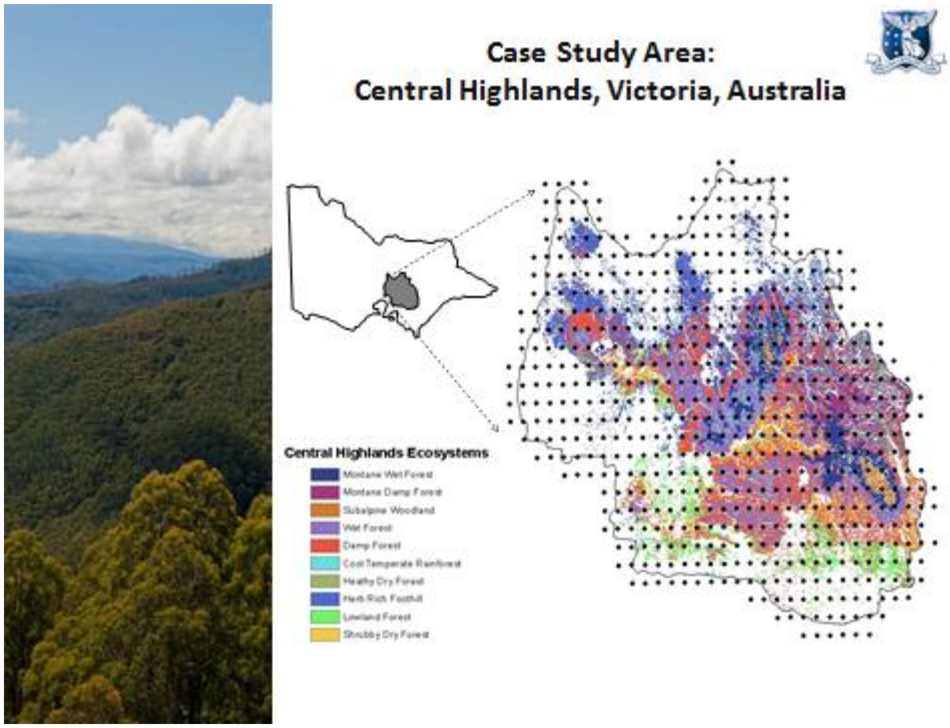


Figure 4.10: CHR Study area. Points represent the spatial grid of climate data used in analysis.

4.4.3 Materials and Methods

Modelling

In this study we used three models to model the response of species and ecosystems to climate change. The meta-model was then used to assess the impacts of adaptation strategies on mitigating the impacts of climate change on forest services. The first model used in a mechanistic model of species regeneration is called **TACA-GEM** (Germination and Establishment), which has been developed to model the suitability of a site for species regeneration and survival (Nitschke and Innes 2008; Nitschke et al. 2012; Mok et al. 2012; Rawal et al. *in press*). The second model used is **TACA-GAP** (Growth and Productivity), which is a combination of the TACA-EM (Nitschke et al. 2012) and BRIND models (Shugart and Noble 1981). This model was use to estimate the Annual Net Primary Productivity and maximum biomass that a species can achieve on a given site given climate and soil parameters. The third model used is the landscape dynamics model **LANDIS-II,** which is a spatial forest simulation model of ecological processes including succession, seed dispersal, disturbances, and climate change (Mladenoff 2004; Scheller and Mladenoff 2004). TACA-GEM was used to provide the regeneration parameters and TACA-GAP the productivity parameters for LANDIS-II under historic and future climate scenarios.

Climate and Climate Change

The climate data was used to select climate inputs for TACA-GEM, TACA-GAP, and LANDIS-II. For TACA-GEM and TACA-GAP, daily weather data representing the years 1960–2000 were analysed using a rank and percentile test which yield 10 historical years of climate data for each climate point (see Figure 4.11) that were then used as the historical climate scenarios in the analysis (Mok et al. 2012). The 10 years of data represent the 90th, 75th, 50th, 25th and 10th percentiles for both observed annual precipitation and mean annual temperature. For LANDIS-II, climate data from 1960-2000 from the established Bureau of Meteorology weather stations in the study area were used to generate a fire weather database with 15000 daily records of wind speed, wind direction, fine fuel moisture codes, build up index, and fire weather index for each station. The latter three parameters were calculated from daily climate observations using the Forest Fire Weather Index (FWI) component of the Canadian Forest Fire Danger Rating System (Van Wagner, 1987). Following Sturtevant et al. (2009) the calculated FWI values were classed into five fire size bins to be used in fire size modelling. A direct adjustment approach was then used to downscale temperature and precipitation from the global circulation model predictions to observed climate on a monthly scale (Mok et al. 2012). Six climate change model/ scenarios were tested – they were: (1) CSIROmk3.5 A1B, high sensitivity; (2) CSIROmk3.5 A1B, low sensitivity; (3) CSIROmk3.5 A1F1, medium sensitivity; (4) BCCRBM2 B1, low sensitivity; (5) CCR-MIROC-H B1, low sensitivity; and, (6) CCR-MIROC-H A1B, medium sensitivity. The envelopes of climate change predictions for the aforementioned scenarios are summarized in Figure 4.12. The response of species and fire to the range of climate and climate change scenarios were averaged for species and amalgamated for incorporation into LANDIS-II.

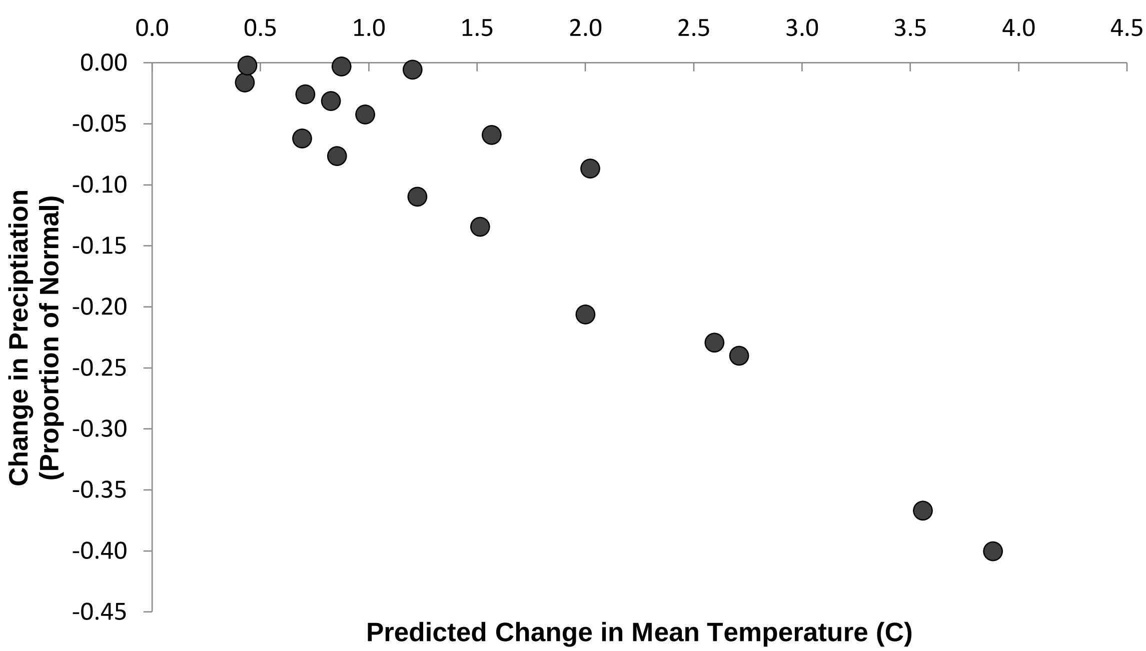


Figure 4.11: Range of climate change incorporated into the modelling

Management

To model the impacts of forest management on a species response to climate change and the impacts of adaptation strategies, the study area was demarcated in to a series of management zones that reflect the current zoning policy as outlined by the Regional Forest Agreement Act 2002.

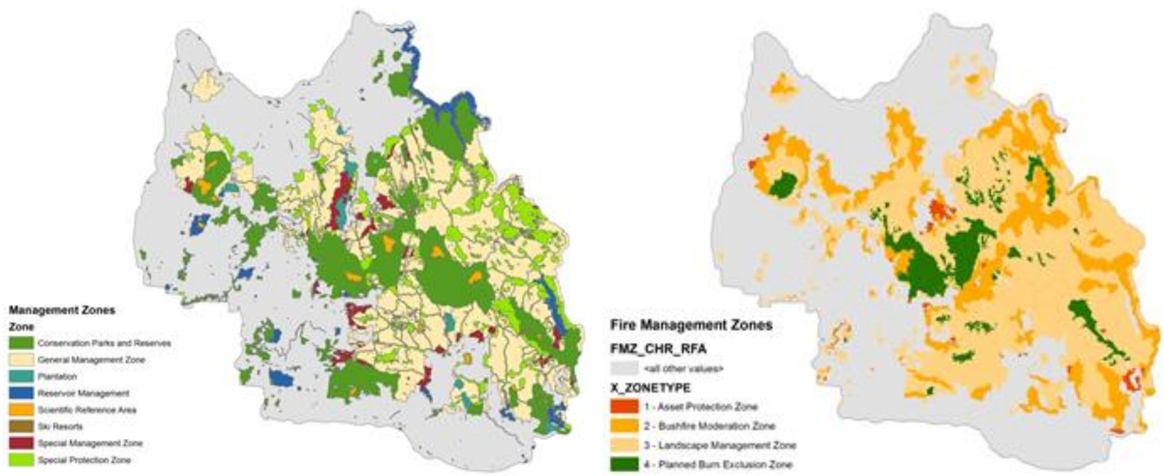


Figure 4.12: Forest and Fire Management Zones used in the modelling of forest management activities.

Management strategies were developed by local forest managers and Masters of Forest and Ecosystem Science students to try and to address the impacts of climate change and maintain the current range of ecosystem services. The services addressed were timber production, water production, carbon stocks, and habitat for Leadbeater's possum (*Gymnobelideus leadbeateri*) (LB Possum).

5.4.4 Results and Discussion

Modelling was conducted on 32 tree species, however the results will focus on the most important tree species *Eucalyptus regnans* F. Muell. *E. regnans* is the most sought after species for timber production, but also plays a dominant role in water production, carbon stocks in the region, and as habitat for Leadbeater's possum. Figure 4.13 illustrates the potential impact of climate change on the species regeneration and fundamental niche. The species was modelled to have its regeneration niche and productivity niche contract to higher elevations, however the contraction in the regeneration niche was far greater than the fundamental niche, which highlights that regeneration may become more limiting under climate change then growth.

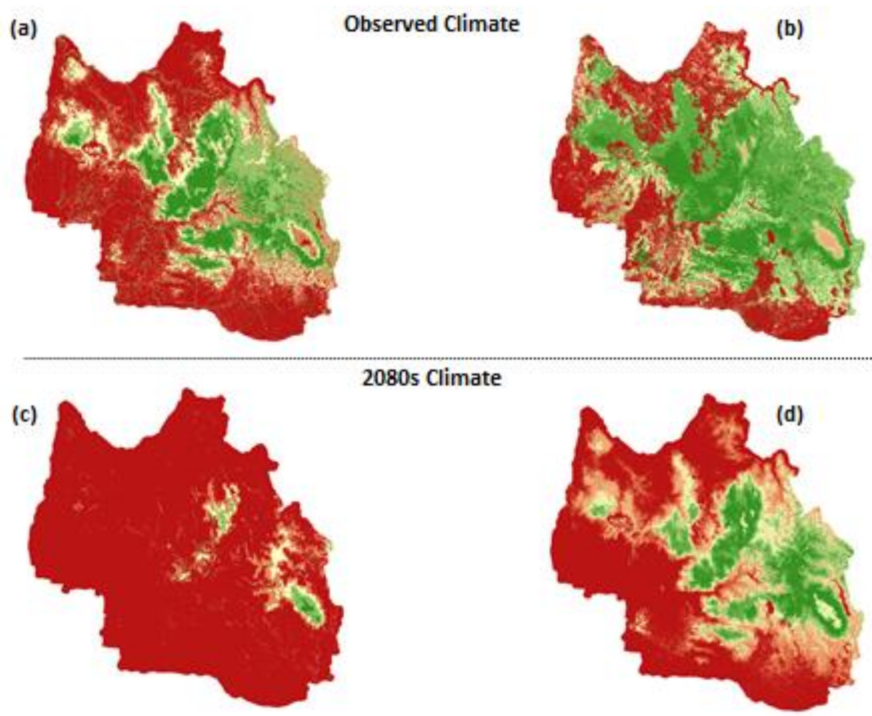


Figure 4.13: Regeneration (a, c) and Productivity (b, d) results for E. regnans under historic (a, b) and 2080s climate change (c, d). Red to Green Scale indicates increasing suitability for growth and regeneration. Maximum regeneration score equals 1.0 and maximum productivity equals 1250 tonnes biomass per hectare.

Landscape modelling of the impacts of climate change on *E. regnans* forests could results in a 48.2% (+/- 2.1%) decline in the species distribution compared to a 6.7% (+/- 1.9%) decline that may occur without climate change over a 200-year period. The modelling also identified areas on the landscape where *E. regnans* remains resilient to climate change. Figure 4.14 summarizes the spatial impact of climate change on this species, but also the impact of management, fire, and climate change on the growth stage distribution. As much of the resilient areas are located in protected areas, the effect of management is negligible, though a recruitment bottleneck is evident under climate change.

The impacts of climate change on the production of the four ecosystem services are highlighted in Figure 4.15. The general trends are a collapse in the amount of timber that can be harvested, and in the amount of LB Possum habitat under climate change. Water production and carbon stocks both increase over time as the forest ages and ash forests transition to dry eucalypt forests that use less water.

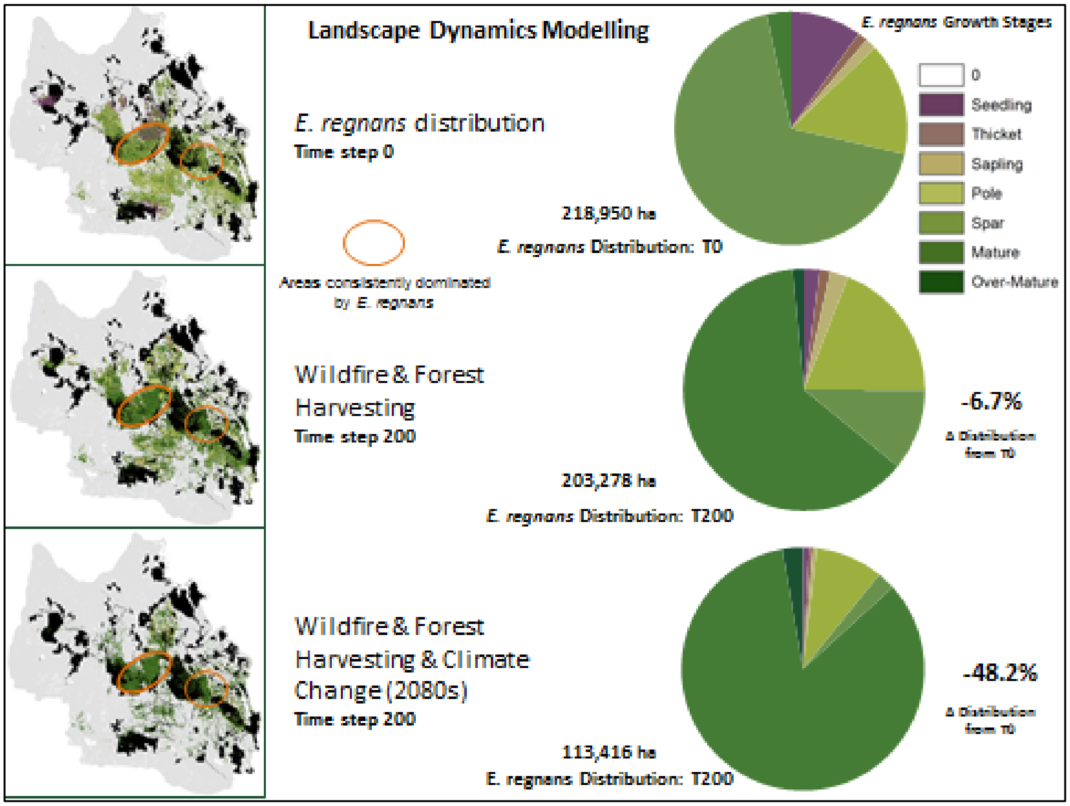


Figure 4.14: Landscape distribution and dynamics of *E. regnans* under a factorial of management and climate change. Recruitment bottleneck is evident in bottom chart and orange circled areas indicate areas of potential resilience. Black areas indicate protected areas (parks or special protection zones).

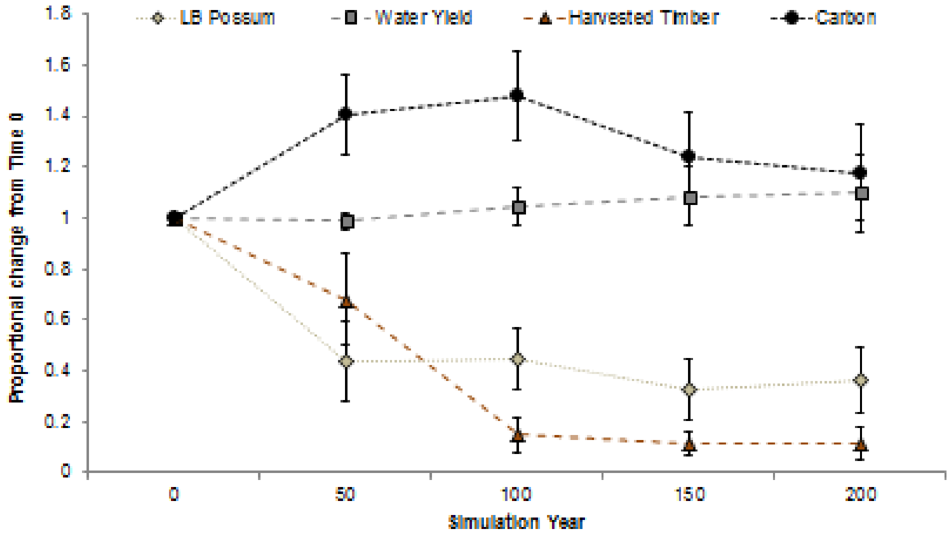


Figure 4.15: Model outputs compare the Wildfire & Forest Harvesting & Climate Change Scenario (Replicated 6 times) to the Wildfire & Forest Harvesting Scenario and show the trends in services over time standardised. LB Possum: Leadbeater's Possum Habitat Based on habitat model that includes presence of 150 year old Ash within 100m of Acacia (relates shelter and foraging habitat with normal home range of LBP). Water: Kuczera model was used to calculate water yield based on proportion of ash age classes on landscape. Water yield assumed constant from other forest types. Carbon: amount of tree biomass on landscape * 0.5. Biomass is direct output from LANDIS-II. Harvested Timber: based on amount of Ash Species (Mtn Ash, Alpine Ash, Shining Gum, Messmate) biomass harvested on the landscape.

Adaptation

A baseline (B1) and 12 alternative (A1-A12) management scenarios were developed and modelled to test the interaction between management, climate change, and the four ecosystem services: timber, water, carbon, and habitat. The outcomes of the scenarios were compared in two ways: (1) Year 200 in simulation to Year 0; and, (2) Year 200 in scenario simulation versus an environmental baseline scenario (climate change and fire but no management). The results were standardized to a proportion of change versus the comparison with 1.0 equalling no loss in the service, greater than one a gain, and less than one a loss in the provision of the service. The scenarios ranged across the spectrum of preservation to timber exploitation; for example some scenarios involved halting all native forest timber harvesting and focussing timber production in exotic plantations, while other scenarios harvested native forest in existing national parks under the context of ecological thinning and fuel management. Figure 4.16 illustrates the trade-offs between services when compared to the two baseline conditions. Irrespective of the baseline condition, no scenario was able to maintain all services under climate change, and thus no Pareto Optimum solution was achieved.

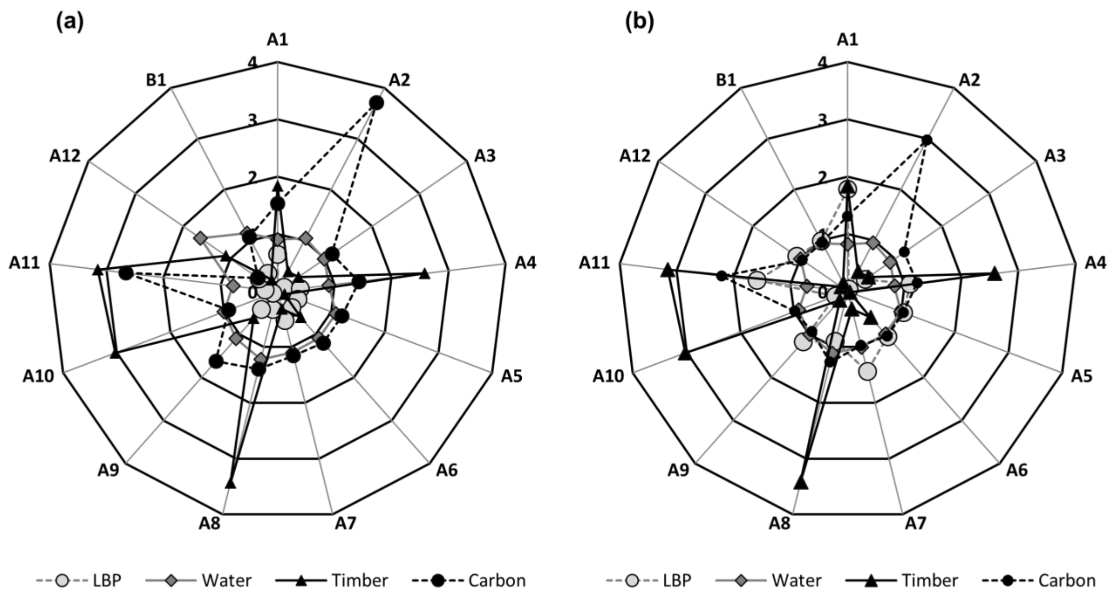


Figure 4.16: Trade-offs between ecosystem services at year 200. Outcomes have been standardized to proportion of change compared to Year 0 (a) or Year 200 in an environmental baseline scenario (b). The Pareto Optimum solution in any scenario is a score of one or greater for all four services.

No scenario was able to maintain LB Possum habitat compared to Year 0, and the B1 scenario was unable to maintain current timber supply. The scenario that performed the best under both metrics was Scenario A1. This scenario was unable to maintain water production (score of 0.90) under both metrics, but was able to maintain carbon, timber, and LB possum habitat compared to the environmental baseline (Figure 4.16b). Scenario A4, A8, and A11 performed well for timber, carbon, and LB possum compared to the environmental baseline, while A8 also increased water production, however all three scenarios harvested in National Parks which would be socially unacceptable. All three scenarios also resulted in less LB Possum habitat compared to A1 in the Year 0 comparison, which suggests that they do a poor job at maintaining habitat. Some conservation oriented scenarios such as A7 and A9 managed to maintain LB possum habitat and water production compared to the environmental baseline, but lost timber production, while the preservation orientated scenario A2 managed to increase carbon stocks and maintain water production, but drastically reduce LB habitat and timber production. Scenario A1 is thus the most plausible scenario for facilitating adaptation to climate change on the CHR landscape and comprised the following actions:

1. Intensified management in 20% of the General Management Zone (GMZ)
2. Maintain pine plantations for wood production
3. Extensive management in the Special Management Zone and remaining 80% of GMZ
    - No harvesting of trees > 115 years old
4. Maintain current reserve policy
5. Plant both *E. regnans* and *Acacia* spp. following harvesting (future habitat for LB Possum)
6. Plant *E. regnans* at higher elevations (Assisted Range Expansion) following harvesting of *E. delegatensis* stands

4.4.5 Conclusions

The case study for the Central Highlands region of southeast Australia has identified that current forest communities that are heavily dependent on timber, water, carbon, and habitat production are vulnerable to climate change. Adaptation strategies that maintain all services are unlikely however, and for some services (timber and habitat) climate change will overwhelm adaptation options when compared to our current baseline. When compared to the level of service provisions in the absence of management, there are adaptation options that could increase habitat and timber supply. The results highlight that vulnerabilities of key forest types/ tree species may overwhelm adaptation if our targets are based on the present not the future, and cast a shadow of doubt on the maintenance of the sustainably managed *E. regnans* forests of the Central Highlands under climate change.

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4.5 Model Integration for Decision Making in a Changing Climate in the Asia-Pacific Region

By Qinglin Li and Brad Seely, Department of Forest Resources Management,
University of British Columbia

Climate change is likely to have profound effects on forest ecosystems, and may disrupt the sustainable flow of their goods and services. Forest species composition is expected to endure considerable change over the next century simply due to climate-driven northward and upward shifts of tree species' distributions. Moreover, the changing climate may have an overwhelming influence on forest phenology, growth and productivity, and life cycles of insects and diseases. Extreme climate events, which appear to be increasing in frequency, can also have negative impacts on forest health. Forest-based services and non-timber forest products are at risk from climate change as well, while social impacts will be more diverse and uncertain. These factors are posing challenges to sustainable forest management (SFM) at local to regional scales. The biophysical impacts of climate change will certainly have deep implications on communities' social, economic, and cultural benefits, especially for forest dependent communities and Aboriginal Peoples.

The overall objective of this research was to assemble existing science, technology, and essential tools to help managers and decision makers make sound decisions on sustainable forest management under the changing climate. There are numerous tools/models used in SFM, strategic planning, and scenario testing to assist high-level decision-making. We explored the potential implications of these models in the Asia-Pacific with the expectation that some of these tools would be adopted by other regions to solve local management issues in a cost-effective manner (see Table 4.3).

Another objective of the study was to develop a set of indicators for which SFM can be successfully evaluated under climate change. We selected 7 indicators from many others for our study region as major indicators that might have a greater response to climate change. Those indicators include: 1. Changes in area of forest distribution, 2. Changes in major climate variables, 3. Suitable species habitats, 4. Total growing stocks, 5. Area of forest disturbed by causes (naturally climate related), 6. Net change in forest ecosystem carbon, and 7. Forest ecosystem carbon storage.

A conceptual framework was developed to integrate models explored in the study to provide high-level SFM decisions (Figure 4.17). There are three main components of this framework – the first component is the appropriate indicators and their models. In this study, we proposed seven climate related indicators designed to be representative of key forest management objectives. For example, forest growing stock may increase due to increased air temperature or elevated atmospheric CO_2 fertilization, and at the same time, it is an important resource for forest management to use to meet social and economic livelihood of the community. In contrast, the indicator, changes in major climatic variables, may not directly contribute to central components for decision-making, but it is critical for other indicators to assess climate change impacts. The second component, an essential part of the framework, is the multiple values trade-off analysis framework for strategic decision-making and planning. All the values/indicators selected or management objectives were formulated in a way that the (sub)-optimal solutions would be achieved through balancing or trading off one value for another/others. The uniqueness of this framework is that the managers or practitioners can quantitatively determine when he/she makes one choice verse another, and what gains or losses they have to face. The last component, intuitive decision support, represents information presentation. Presenting information in a simple way to let common users understand the key points is a challenging task that many researchers are currently facing. It is common that research results are normally communicated within very limited audiences due mainly to the practicality of the research, and the way in which the results are presented. In our framework, we present the results by using simple and intuitive risk classes to assist managers, practitioners, and even general stakeholders to understand the complex forest management issues. It also helps to provide insight as to how the issues were addressed, and the nature of the compromises that must be made when dealing with these issues (Figure 4.17).

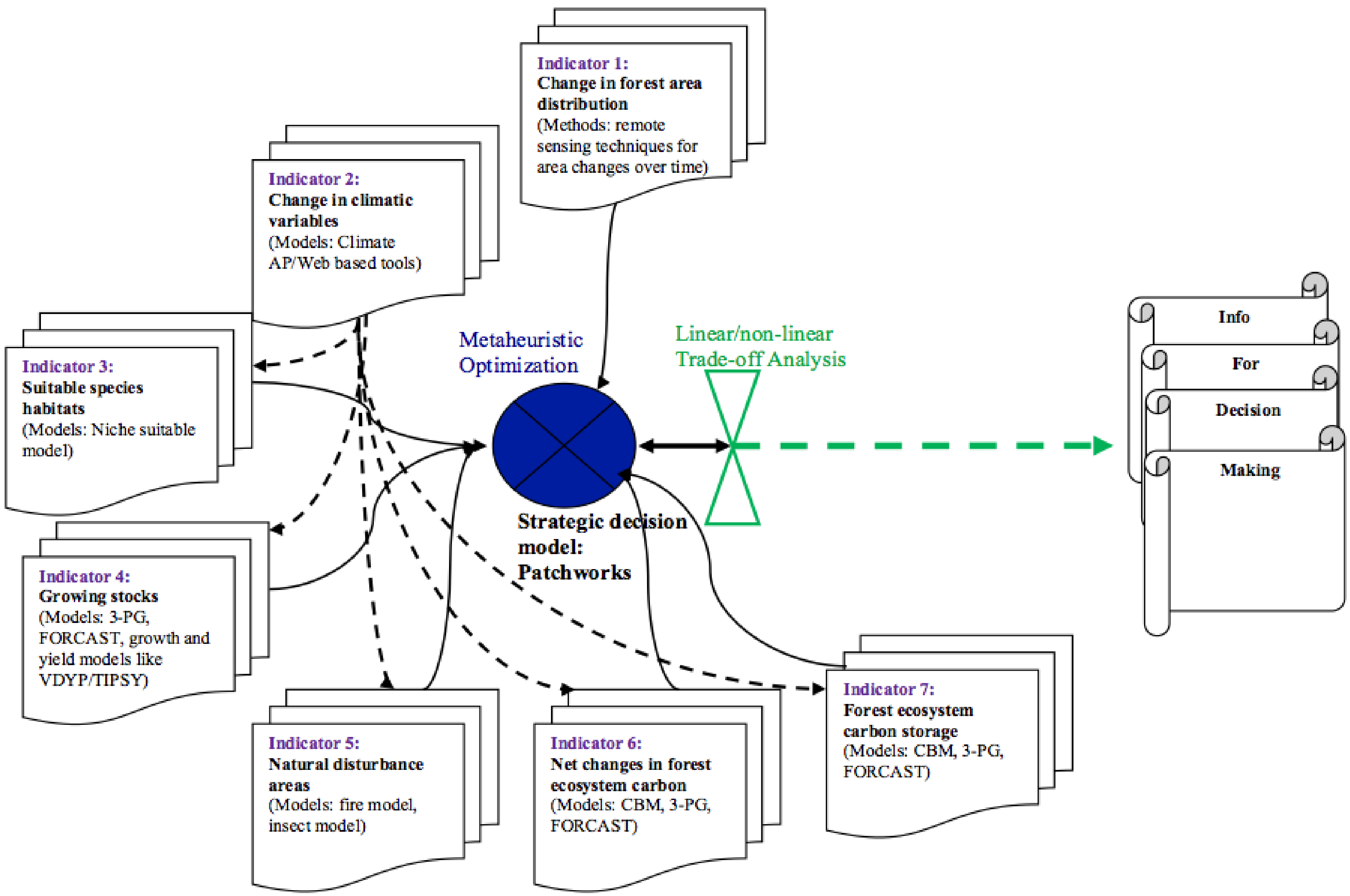

Figure 4.17. A conceptual flow diagram of the indicator-based decision-support framework.

Table 4.3 A summary of the modelling tools employed within the pilot studies.

Model	General Applications	APFNet sites	Spatial Scale	Climate Change	Climate data	Potential Links	References
FORECAST Climate	Forest productivity, growth and yield, forest carbon dynamics, soil fertility, resource trade-off analysis	Coastal BC, Canada; Fujian, China	Stand	Yes	Daily	TACA, LST, Patchworks	Seely et al. 2014
Tree and Climate Assessment tool (TACA)	Species composition, regeneration	Central Highlands, Australia	Stand	Yes	Daily	FORECAST Climate, LANDIS-II	Nitschke and Innes 2008
3-PG	Forest productivity	Mainland China	Stand to medium landscape	Yes	Monthly	LST	Landsberg and Waring. 1997
Carbon Budget Model (CBM-CFS3)	Forest carbon dynamics	Coastal BC, Canada	Stand to regional	No	N/A	Patchworks	Kurz et al. 2009
Landscape Summary Tool (LST)	General framework for scaling up stand-level model output, Resource trade-off analysis	Fujian Province	small landscape	Yes[1]		FORECAST Climate; 3PG	This Report
LANDIS-II	Species composition, succession	Central Highlands, Australia	small to medium landscape	Yes[1]	Monthly	TACA	Scheller et al. 2007
BEPS-TerrainLab v.20	Forest hydrology and related biogeochemical processes	Coastal BC, Canada; Fujian, China	small landscape	Yes	Daily		Govind et al. 2009

Model	General Applications	APFNet sites	Spatial Scale	Climate Change	Climate data	Potential Links	References
Patchworks	Forest planning, growth and yield, natural disturbance	Coastal BC, Canada	small to medium landscape	No	N/A	FORECAST Climate, CBM-CFS3	Lockwood and Moore, 1993
Climate AP & Web tools	Spatial downscaling of climate change data	Asia Pacific Region	medium to regional	Yes	Monthly	FORECAST-Climate; 3PG, TACA	This Report
Climate AP & Niche models	regional, species-specific, climate suitability analysis	Asia Pacific Region	medium to regional	Yes	Monthly		This Report

Chapter 5 – Development of web-based tools

By Tongli Wang, Department of Forest and Conservation Sciences, University of British Columbia
Guangyu Wang, John Innes and Min Zhao, Department of Forest Resources Management, University of British Columbia

5.1 Background

The internet has profoundly changed the way people get information. If a piece of information or a database is accessible through an internet browser, it means that the information or the database can be delivered to users' finger tips. The objectives of this part of the project include:

1) A project website that serves as a window to the project, including the research objectives, organization, research team members, events, etc.;

2) The map-based ClimateAP to provide interactive access to scale-free climate data by clicking on the Google Map through a browser; and

3) Spatial visualization of climate maps and spatial projections generated from output of ecological models.

5.2 Methods

We used WordPress to develop our project website. We followed the WordPress template provided by the University of British Columbia (UBC). The website is hosted at UBC.

For the map-based ClimateAP and the spatial visualization tools, we used Microsoft Visual Studio ASP.Net and Google Map API (Application Programming Interface). Although internet maps are available from different sources, the complete set of functions that we needed for our objectives were only available from Google Maps.

5.3 The tools

5.3.1 The project website

The project website can be accessed at: http://asiapacific.forestry.ubc.ca/

Figure 5.1 shows the Home page and items covered at the website. At the completion of the project, some outputs will be linked to this website.

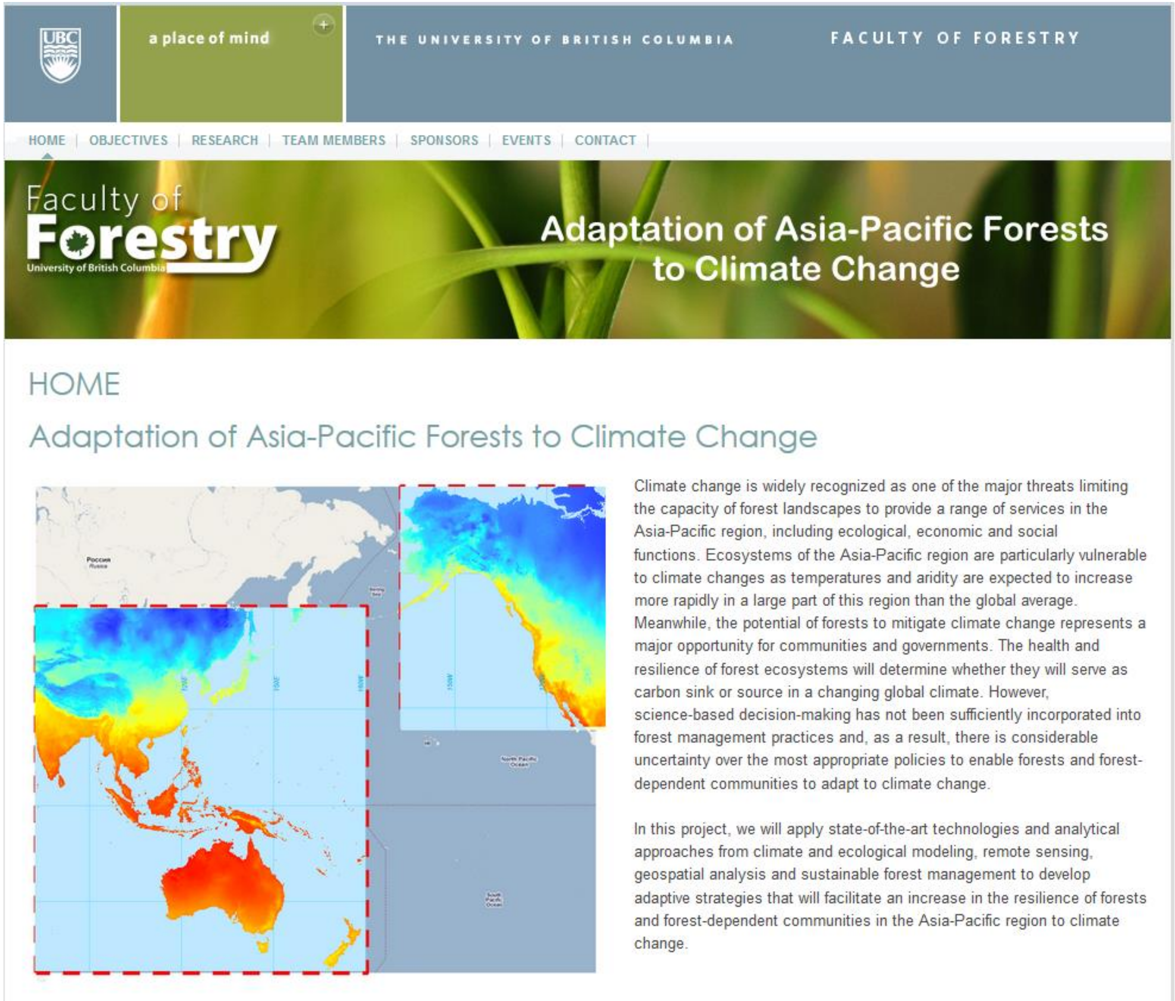

Figure 5.1 The Home page and items covered at the website.

5.3.2 Google Maps based ClimateAP

The Google Maps based ClimateAP has the full function of its desktop version except that it only allows access to climate variables for one location each time. However, it has several additional features over the desktop version:

- No input data is required. The desktop version requires users to input coordinates (latitude and longitude) and elevation for the location of interest. For the map-based version, a user just needs to click at the location of interest on the Google Map. Then, the program will obtain the coordinates and elevation of the location automatically.
- The location of interest can be precisely located on the map and errors in the coordinates and elevation can be avoided.
- The climate conditions of the location can be visualized in the context of the climate conditions around.
- No downloading and installation are needed.

The interface of the map-based ClimateAP can be accessed at http://climateap.net/. Its interface is shown in Figure 5.2. A quick tutorial can be found at http://climateap.net/help/tutorial.pdf.

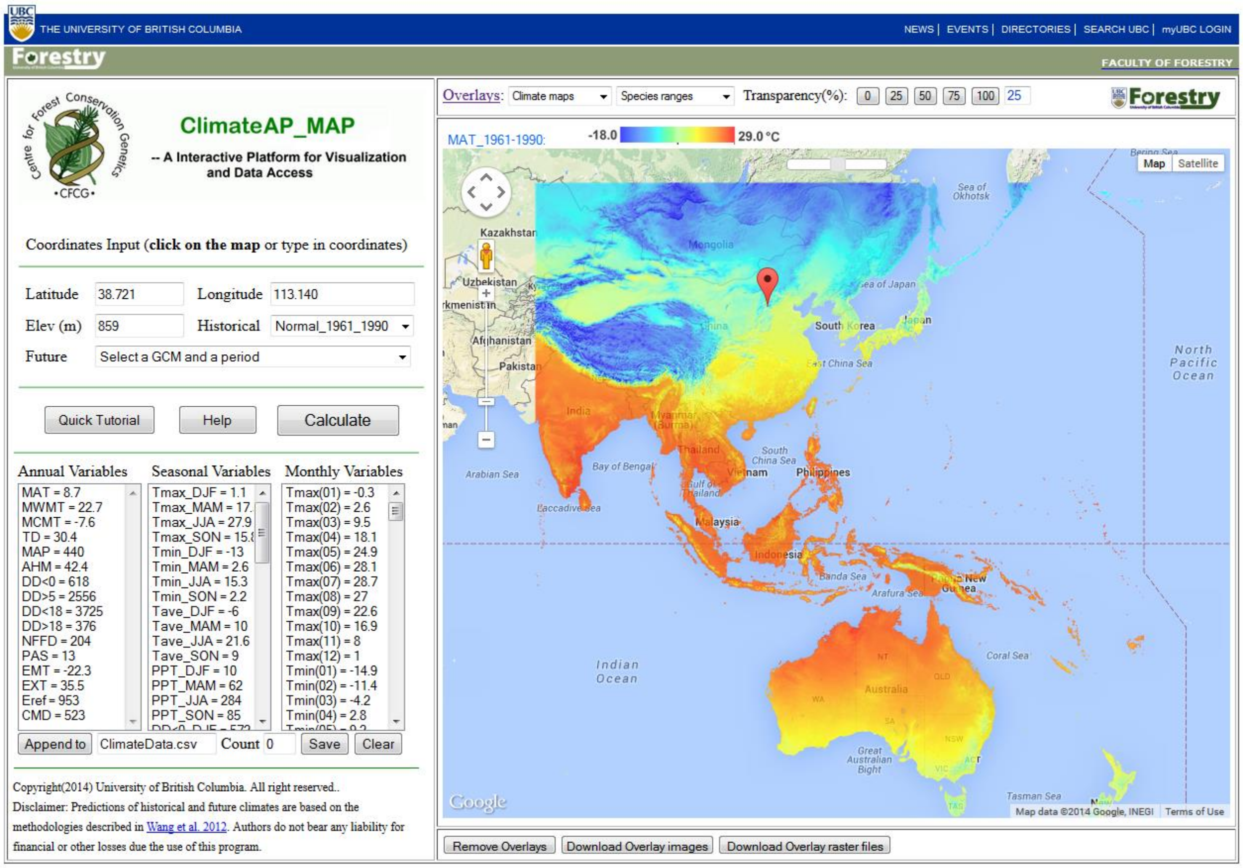

Figure 5.2. The interface of the Google Maps based ClimateAP.

5.3.3 Google Maps based spatial visualization tool

We overlaid maps of some important climate variables generated using ClimateAP (Chapter 2), and maps of consensus projections generated from the climate niche models of five important species (Chapter 3). The map overlays allow spatial visualization of the outputs from this project. Users can take advantage of the features provided by Google Maps, zooming into a specific site of interest or zooming out for a broader view of the big picture. Users can also change the transparency of the overlays for different visualization objectives. In addition, users can download the overlay maps either in graphic or GIS format. The interface of the tool and an example of an overlay map for Chinese fir is shown in Figure 5.3.

As this tool is integrated with ClimateAP, users can access climate data while visualizing the overlay maps. These tools will provide scientists, stakeholders, and policy makers easy access to up-to-date information and knowledge on climate change in this region.

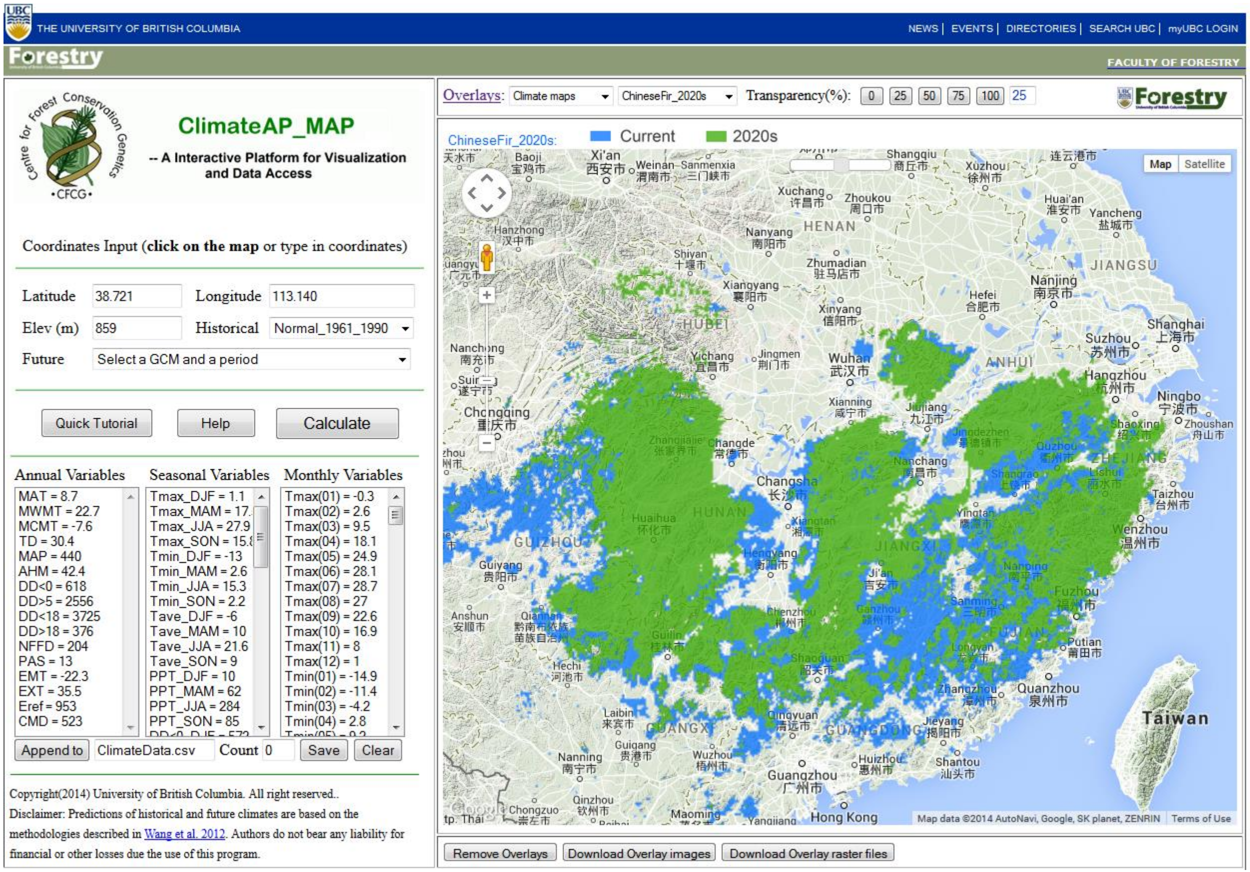

Figure 5.3. An example of an overlay map for Chinese fir.

Chapter 6 – Communication and network building and technology transfer

By Guangyu Wang, John Innes and Shari Mang, Department of Forest Resources Management, University of British Columbia

6.1 Background

Network building is a key for stakeholder participation, communication, and contribution to forest adaptation to climate change in the Asia-Pacific region. The development of a scientific network that consists of a group of competent and high quality researchers will be imperative for APFNet to achieve its goals. We have already built up a substantial network based on past collaboration in this region, particularly between China, Australia, and USA. This network has been intensified and expanded during this project through knowledge transfer, interviewing stakeholders and policy makers, personnel exchange, and organizing workshops to train scientists. Additionally, we have kept our collaborators updated on the project's progress through reports and policy briefs, such as the brief written for government bodies throughout the Asia-Pacific (See Appendix 6.1). This networking has facilitated the capacity building and knowledge transfer components of the project, as well as supported and strengthened decision-making regarding forest management responses to climate change.

6.2 Network building

The project formed a great research team and advisory committee. The advisory committee members consisted of climate and forest research experts in the Asia-Pacific region from Canada, China, the US, Australia, Malaysia, and Indonesia. The research team members were from universities, government agencies, and research institutes.

The network was built gradually through various activities including events held at The University of British Columbia (UBC), Canada (Climate Change Adaptation - Sustainable Forestry Management Workshop) and in Yichun, Heilongjiang Province, China (International Conference on Response of Forests and Adaptation Management to Climate Change), which were designed for the project, and invited experts from over the world to discuss the nature of the project and knowledge gaps that may exist (Table 6.1). Additionally, project team members attended international meetings and conferences such as the Asia Pacific Forestry Commission in New Zealand, the Sustainable Forest Management Conference in Malaysia, and the Ecosystem Services Conference in Costa Rica, where they discussed the project's research as a means of achieving practical solutions to management and adaptation problems, and enhancing ecosystem resilience. In the initial stages, the project management team members visited pilot sites and also formed the local communication network. The expert network and communication with local and forest communities were further expanded and enhanced throughout the progression of the project.

Table 6.1 A summary of the number events and people involved in network building activities.

Item	Number of Events	Total number of people involved	Duration
Visiting Delegates	12	280	Less than a week
Training and Workshops	4	350	One week
Academic training, graduate students and visiting scholars	6	6	3 months and up
Conferences	7	380	Half day seminars
Seminars	16	860	Half day seminars

Research seminars were also conducted at several universities and research institutions to audiences ranging from 50 to 120 people. These events were aimed not just at academic audiences, but also presented to government bodies as a way of connecting them with the research and tools produced by the project, so that they may be aware of the importance and urgency of climate change adaptation and of the tools available for them to act. The research seminars were half-day presentations held in conjunction with other local research presentations. The presentations were targeted towards the local region, with the topics and tools discussed being relevant to the adaptation of the local ecosystems. These events contributed significantly to the project's successful networking, and were an essential means of expanding the scope of the network beyond academic researchers to include government agencies and industry.

Team members participated in 16 seminars over the duration of the project, which benefited approximately 860 participants (Table 6.1). The location of these seminars is as follows: in Malaysia: Universiti Putra Malaysia; in India: Indian Forest Service; in Taiwan: National Taiwan University, National Taiwan Normal University, Taiwan Zhongxing University, Jiayi University, Ilan University, and the Taiwan Forestry Bureau; in Mainland China: Northwest Agriculture and Forestry University of China, Nanjing Forestry University, Fujian Agriculture and Forestry University, Hebei Agriculture University, Xiamen University, and the Chinese Academy of Forestry; in Australia: University of Melbourne; in Canada: University of British Columbia.

UBC hosted six visiting scholars from multiple universities in China (Table 6.1). Their length of stay varied between 3 to over 17 months. They worked with members of the research team at UBC, and audited several courses covering such topics as Forestry in British Columbia, Forest Stand Dynamics, Technical Communication Skills, and Scientific Writing. This exchange opportunity strengthened the relationship between team members and increased collaboration on research, bringing together knowledge from different backgrounds and forestry practices to yield the best possible results.

The network of scientists, stakeholders, and policy makers from across the Asia-Pacific region allowed this project to achieve APFNet's goals of capacity building and information exchange. The international collaboration strengthened the project team and benefited the researchers, institutions, and countries involved, through an immense transfer of knowledge and skills regarding tools, technology, and management planning.

6.3 Workshops

A training workshop was held in Kunming, China from July 1, though July 11, 2013. A training handbook (119 pages) was assembled for participants, which included an overview of the issues and challenges for forestry in the Asia-Pacific region, touching on statistics and trends of forestry activities, management, and policy information, the challenges resulting from climate change, and forest management strategies for climate change adaptation and mitigation. Details can be found in Appendix 6.3.1

Tools to aid in sustainable forest management were a focus of this workshop. Participants were guided through a framework to develop and apply the most useful and appropriate models to achieve the desired knowledge outcomes when being applied under various conditions. The development, application, and relevance of several tools and models developed and utilized in this project were presented at the workshop. This included: conventional growth and yield models; ClimateAP; carbon budget models; LANDIS-II model; climate niche models for ecosystems and species; FORECAST Climate; TACA-GEM model for species regeneration. The workshop also involved hands on fieldwork related to collecting and assessing data sources to implement models, giving participants a chance to improve their skills using these tools. Forest management strategies for adaptation and the potential impacts of climate change were also discussed in the context of the tools and data they were using.

This workshop allowed the outputs and technological advancements made by this project to become available to some of the research community in the Asia-Pacific. Additionally, the report *Sustainable Forest Management in a Changing Climate* (144 pages) was produced as a compilation of 10 reports from participants of the workshop on topics relating to management and climate change adaptation of forests in their country. The booklet is publicly available, and can be found in Appendix 6.3.2.

6.4 International Union of Forest Research Organizations World Congress

Team members from this project co-organized a policy-training program and carried out at the International Union of Forest Research Organizations (IUFRO) World Congress held October 5-11, 2014 in Salt Lake City, USA. A poster summarizing the accomplishments of the project was presented. Additionally, three project team members made presentations focusing on: ClimateAP and its use in projecting the climate niche and productivity of forest trees in future climates in the Asia-Pacific; Climate change impacts in the temperate forests of Southeast Australia: can forest management reduce vulnerabilities?; A multiple values trade-offs framework for climate change adaptation.

The presentations made by members of the research team at IUFRO were well received. This event was an excellent opportunity to make the international forestry community aware of this projects achievements, and receive feedback which will be beneficial for the work done during the second phase. Attending the IUFRO World Congress broadened the network of this project, facilitated information exchange in both directions, and promoted sustainable forest management to help mitigate and adapt forests to climate chance, which are in line with the overall objectives of APFNet.

6.5 Survey of Experts' Opinion

A questionnaire was developed and distributed to experts in the field of climate change and forestry, including government officials, professors, researchers, and community and Non-Governmental Organizations, from countries throughout the Asia-Pacific region. The main objectives of the survey were 1) to study experts' perspectives and knowledge on the impacts of climate change and forest adaptation in the Asia-Pacific region, 2) to explore the implications/recommendations for adapting forests to climate change in the Asia-Pacific region, and 3) to identify the challenges this with pose. The information gathered was also intended to provide support for further research in developing climate and ecological models, developing adaptive tools and strategies, and establishing a cooperative network of information sharing for sustainable forest management and rehabilitation in the Asia-Pacific region (See Appendix 6.5).

6.5.1 Methods

Questionnaire Design and objectives

The questionnaire consisted of qualitative and quantitative research questions based on four leading research questions, with several subsequent questions, aimed at achieving the aforementioned objectives. The leading questions were as follows: 1) What are the main impacts of climate change in the Asia-Pacific region?, 2) What are the availabilities of climate change related actions/policies in the Asia-Pacific region?, 3) What are the challenges for adapting forestry to climate change in the Asia-Pacific region?, and 4) How can current actions to adapt forestry to climate change be improved? Additionally, participants were asked general information about themselves in order to categorize them within the proper professional position and home country.

Sampling and Analysis

Prior to distribution, a pre-test was completed with 15 people. Sampling was conducted in two ways – paper-based questionnaires and an online survey. The paper-based questionnaires were distributed to and collected from attendees at three international conferences, namely Sustainable Forestry Management in A Changing Climate in Kunming, China; 25th session of FAO Asia-Pacific Forestry Commission in New Zealand; and Asia Forestry Summit in Indonesia. The remainder of the participants were contacted via email, and could complete either the attached electronic version of the questionnaire, or an online survey, both of which were identical to the paper questionnaire. In total, 220 questionnaires were distributed starting July 2013, and 78 questionnaires were collected by August 2014 across 23 countries, giving a response rate of 35.0%. One invalid questionnaire, only two-thirds complete, was eliminated during data analysis.

To analyse the data and determine regional differences, respondents were grouped into five regions including South Asia, Southeast Asia, Eastern Asia, Oceania, and the Americas. Guidelines from the FAOSTAT website (http://faostat.fao.org/site/371/default.aspx) were used to determine the region in which participants would be placed. Additionally, respondents were groups into one of the four professional positions previously mentioned, according to their response to the general information questions. The collected questionnaires were input into the software Statistical Package for Social Science (SPSS), version 22. A one-way ANOVA was used to compare the different regions or different professional positions for the different concerns about climate change.

6.5.2 Results/Discussion

Impacts of Climate Change

Although there were some disparities, forest and water related issues were among the top three concerns regarding the negative impacts of climate change. Interestingly, the melting of sea ice was ranked as the lowest concern overall, and among many regions and professions, however its related consequences such as flooding and rising sea levels were among top concerns. Some regional differences were observed such as high concern regarding drought in Eastern Asia, Oceania, and the Americas, while South Asia and Southeast Asia ranked flooding to be of highest concern. These differences may be explained by the high heterogeneity throughout the Asia-Pacific leading to different regions being more susceptible to various impacts depending on their geography, topography, local climate and ecosystems, and socio-economic situation.

Forest related changes were indicated to experience the most positive impacts due to climate change from both the regional and professional perspectives. This was expressed through the selection of land productivity and rate of forest growth as being the top positive impacts. A high proportion of participants from all regions, excluding the Americas, indicated they did not know what the positive consequences would be. The high response to positive impacts by the Americas' participants may be due to their geographic location, as positive impacts are more likely to occur in higher latitudes (IPCC 2013).

There was consensus, both regionally and professionally, that the economic sector of most concern was agriculture followed by forestry, with high variability observed for all other sectors. When asked specifically about the important impacts of climate change on forests, respondents indicated the top concerns to be changes in biodiversity and forest fire/drought. Similar levels of concern were observed between several other options, including land suitability changes, forest productivity changes, and changes in pest outbreak. This pattern was fairly consistent across the regional and professional analyses. However, higher biodiversity changes among developing countries (i.e. South Asia, Southeast Asia, East Asia) compared to higher forest disturbance related impacts among developed countries (i.e. Oceania, America) represents an unexpected difference between these regions. Since forest disturbances contribute to the shift of forest ecosystem and the loss of biodiversity (Allen et al. 1998), the difference possibly suggests that forests in developing countries have experienced longer and more significant impacts under climate change compared to developed countries, which may indicate that developed countries are more capable in adapting to climate change.

Climate Change Related Policies and Strategies

Respondents were asked to indicate their involvement in international climate change related actions or initiatives. High involvement in the Kyoto Protocol (33.2% of respondents) was observed, and expected, since as of 2013, 192 parties had agreed to the emissions reductions targets outlined in the Protocol (UNFCCC 2014). Surprisingly, the lowest involvement among all regions and professions was with the International Strategy for Disaster Reduction (5.9% of respondents). Although it was not listed as an option, REDD+ was indicated by many respondents via the 'other' category as an initiative with which they were involved. Satisfaction among respondents regarding these international initiatives averaged at 3.18 on a 1 (very satisfied) to 5 (not satisfied) scale, with lower mean satisfaction in Southeast Asia, and higher mean satisfaction in Oceania and the Americas. Specifically, only 1.32% of respondents were very satisfied, while 14.47% were not satisfied at all with the outcomes of international initiatives.

Participants were then asked about the availability of climate change related actions to adapt forests in their region, and their satisfactions with said initiatives. The majority (73.7%) indicated that these types of actions/initiative were available, however their satisfaction averaged at 2.7 on the 1-5 scale. The satisfaction with the outcomes of these actions and initiatives appeared to be higher in developed than less developed countries, suggesting a better adaptive capacity in developed countries in terms of policy effectiveness, institutional effort, and financial support. Diverse goals, objectives, and scope of the available actions or initiatives often make it difficult for decision-maker to choose the appropriate strategy (Preston, et al. 2011), potentially leading to outcomes that do not meet the desired expectations. Additionally, action plans are often fragmented approaches, which lack comprehensive solutions, lack focus on specified sectors, and do not address long-term mitigation and adaptation of climate change (Preston et al. 2011; Dannevig et al. 2012; Romero-Lankao et al. 2012; Runhaar et al. 2012). Participants' responses indicate that although initiatives are available, there needs to be more diverse, full-scale implementation of policy and strategies throughout the Asia-Pacific region, which will likely lead to more impactful mitigation and adaptation measures, increasing the satisfaction of those involved.

Challenges in Adapting Forestry to Climate Change

Overall, public awareness was indicated as the most challenging issue for adapting forestry to climate change in the Asia-Pacific region, with legislation, lack of scientific guidance, and stakeholders' participation following closely behind. However, there was some diversity in responses. The professionally and regionally based analyses indicated agreement between professors and researchers, and Eastern Asia and Oceania that legislation was the most challenging issue. Government officers, as well as Southeast Asia and the Americas indicated it to be public awareness, while community and NGO workers indicated stakeholders' participation, and South Asia indicated lack of scientific guidance.

When asked specifically about the scientific support available to address climate change, the areas indicated as lacking support were local predicted climate change scenarios, forest adaptation, and ecosystem dynamics. There was variation both regionally and professionally, however local predicted climate change scenarios were consistently ranked high for both analyses.

Through the assessment of the availability, accessibility, and suitability of technologies and tools to adapting the forestry sector to climate change, it was found that 43.4% of respondent agreed that some local climate models had been developed for their region. Of those respondents, only 21.1% deemed them to be suitable for their region. With regards to the availability of forest management tools to address climate change, map-based interfaces for access to climate change related databases and model projections for ecosystem and species distributions were deemed much more available than high-resolution climate models, especially in South Asia, Southeast Asia, and Eastern Asia. The more developed countries in Oceania and the Americas indicated higher availability of these types of tools.

Policies and regulations to promote Sustainable Forest Management were deemed available in most regions, with some disparities. However, some participants commented that even though general management guidelines are available, specific ones are lacking, resulting in challenges for implementing climate change adaptation plans. Precise guideline and adequate management supported by scientific research are needed to provide stronger support to policy makers and forest managers to adapt their practices to maintain healthy, productive forests in the face of climate change.

Lack of legislation and scientific knowledge is a constraint on climate change adaptation for developed (Gardner et al. 2010; Ford et al. 2011; Milfont 2012) and developing countries (Begum and Pereira 2013; Pasquini et al. 2013), and decision-makers are often left with too many uninformed options that make implementation of policy more challenging (IPCC 2013). This was reinforced by the indicated poor suitability of management tools for the region. The availability of forest planning tools was higher in more developed regions, and as such, it was reasonable to see the high demand for high-resolution climate models in the regions with more developing countries. Such a difference in tool availability between developed and developing countries highlight various gaps (e.g. financial, institutional), as well as the uneven adaptive capacity and scientific knowledge throughout the Asia-Pacific region. This needs to be improved to generate suitable and accessible climate adaptation and mitigation strategies. It is important to note that knowledge on climate change was not indicated to lack scientific support, and was consistently ranked as the lowest concern. This highlights that it not a lack of understanding about climate change that is hindering action, but the lack to tools, models, appropriate initiatives, and financial resources (as indicated by several other survey questions) that are impeding the ability to adapt and mitigate.

Comments from Experts

Respondents expressed that the adaptive capacity in the Asia-Pacific region is unevenly distributed, due to differences in knowledge about climate change, available techniques and management tools, effective governance and monitoring, and multi-level cooperative systems. In general, developed countries have stronger adaptive capacity than developing countries (FAO 2010b). The most vulnerable communities are those with high exposure to climatic risks, and weak management and adaptive capacity (Heltberg et al. 2009). Cooperative networks need to be established to allow information, technology, and adaptive skills to be shared among different countries across the Asia-Pacific region to reduce the gap in capacity.

6.5.3 Conclusions

Several key conclusions were observed in this study. Firstly, knowledge and awareness about climate change are essential for adaptation. Climate change adaptation can be constrained by biased perceptions about the associated risks, different cultural preference and value during adaptation, and limited development of technology. Strengthening adaptive capacity through investing in education, increasing information accessibility and knowledge represents a great opportunity for climate change adaptation. Secondly, there needs to be more proactive strategies and action at local levels with more specific goals. Most international initiatives tend to focus on general trends of climate change and target nationwide stakeholders, which may overlook situations unique to the local environmental, social, and economic situation. Thirdly, actions, policies, and technologies generally have low accessibility and suitability in the region, especially for developing countries. Limited accessibility in certain nations constrains their ability to generate coping strategies for specific problems, implement national or local policies, and further their adaptive capacity. Without accessible information, assessments about climate change may be biased, limiting the suitability of policies or developed technologies for the region. Lastly, facilitating adaptation to climate change requires minimizing the gaps of adaptive capacity between the regions countries.

Additionally, this survey has highlighted the importance of the outputs from this project. The research team has been able to address several key concerns raised in this questionnaire, notably increasing scientific support for local predicted climate change scenarios, forest adaptation strategies, and ecosystem dynamics through the models and tools developed. Ecological models for predicting shifts in species' suitable climate niches, and FORECAST Climate provide guidance for forest managers and policy makers to develop better forest adaptations strategies. Pilot site experiments have enabled the development of adaptive strategies for climate change through the integration of model prediction with local forest management practices. As well, the lack of publicly accessible and high-resolution climate models has been addressed through the development of ClimateAP. Additionally, the development of web tools facilitates easy access to climate and ecological models, and other information pertinent to locations throughout the Asia-Pacific.

6.5.4 Recommendations

The diversity of Asia-Pacific countries means that each will need to develop climate change adaptation strategies best suited to meet its needs. Some recommendations were drawn from respondents' opinions and summarized as follows.

Broader stakeholder engagement

Broader stakeholder engagement, especially at the local level, is essential to ensure more successfully implemented policies. Improving local knowledge and awareness about climate change through training and education is an important starting point. Bringing the involved stakeholders to the same level of understanding about climate change should improve the success of the implementation of policies and development of strategies.

Development of technology and management tools

There needs to be development of suitable and accessible technology and management tools for adapting and mitigating climate change in the Asia-Pacific region. This includes high-resolution climate change model, local predicted climate change scenarios, and ecological models assessing specific types of forests and species. Integrating forest management practice with improved local climate change predictions will generate clearer options for local decision makers, and maximize the contribution of forests to mitigating and adapting to climate change.

Establish cooperating network

A network should be established for sharing information, and transferring knowledge and skills among experts with different background. Knowledge and technical support from regional and international partners would enhance local climate change data generation and predictions. Platforms to share information, knowledge, and skills with different experts are needed in order to strengthen and balance the adaptive capacity across the Asia-Pacific region.

Improving the effectiveness of policy

The effectiveness of implemented policy and actions needs to be improved by strengthening governance and monitoring systems at multiple levels. It was suggested that although the policies has been developed, the effectiveness remains limited partly due to poor monitoring systems. Making clear the responsibilities of institutions and other actors during policy implementation is a way to enhance the effectiveness of polices and actions.

6.6 Extended Application of Research Outcomes

Several research initiatives have already been planned that apply the project's research outcomes to some of the prominent forestry and climate change related challenges in the Asia-Pacific. This has been possible due to partnership with international organizations and the funding they have provided. These research topics include investigating insect and tree species distributions under climate change, thanks to the funding provided by the Chinese Academy of Forestry and the Canadian Environmental Assessment Agency, respectively. Additionally, our partnership with the Northeast Forestry University will focus on the relationships between climate change and forest fire. The Northwest Agriculture and Forestry University will be working with us to examine the distribution of vegetation in the Qin Ling Mountains, home to the giant panda. Specifically, this work will investigate how changes in tree species distribution and the impacts of climate change will impact the survival of giant pandas. These partnerships have allowed the research teams' achievements to extend beyond the completion of the project, and will help to transition into the next phase of research.

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Chapter 7 – Extended research activities

7.1 Analysis of Ecosystem parameters

By Baozhang Chen, Nicholas Coops, Department of Forest Resources Management, University of British Columbia

Remote sensing data for Canada, China, Southeast Asian countries, and research sites in the Maple Ridge (Malcolm Knapp) Research Forest and Central Highland were collected and processed. We collected AVHRR (the advanced very high resolution radiometer) imagery data for the whole Asia-Pacific region at 8-km resolution for the period 1982-2006 and MODIS data at 1-km resolution for the period 2000-2011.

The spatial-temporal patterns in normalized difference vegetation index (NDVI) in China are shown in Figures 7.1.1 and 7.1.2. We have found that: (i) At the country scale, a statistically significant positive trend of average NDVI was observed during the entire study period. However, there are two distinct periods with different trends in NDVI (Figure 7.1.2). NDVI first significantly increased from 1982 to 1990, and then insignificantly increased from 1997 to 2006; (ii) About 26% of the research area in China showed a significant trend, most of which was positive. Although most of the research area had a significant positive trend before their turning point, there are large variations in the trends after their turning points; (iii) Climate has been shown to have significant effects on terrestrial vegetation during most months of the year at the country scale. Furthermore, temperature has a greater impact than rainfall on vegetation, whose effects can last up to 3 months; (iv) The annual NDVI of only 14.39% and 10.54% of the research area has a significant relationship with temperature and precipitation, respectively. Considering the impact of different land use types, most of the arable land and lawn had a significant increasing trend in NDVI. Considering the impact of different natural zones, most of the temperate grasslands and alpine flora had significant increasing trends in NDVI. Moreover, temperature had a greater impact on the vegetation of the aforementioned areas than precipitation.

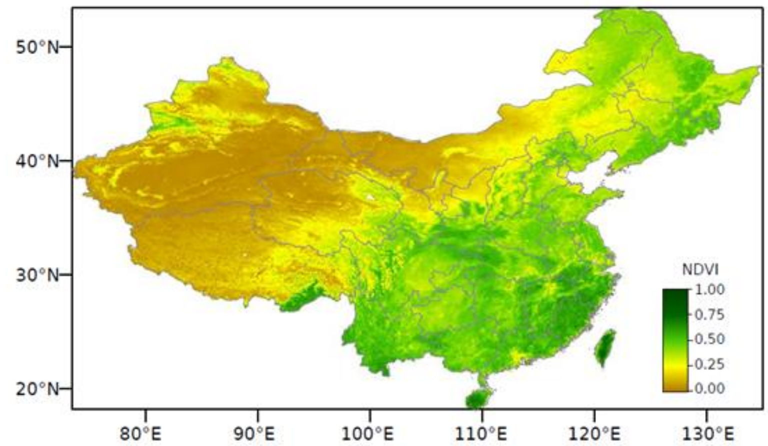


Figure 7.1.1. The mean NDVI of the study area (Southern China Sea Islands are excluded from study area)

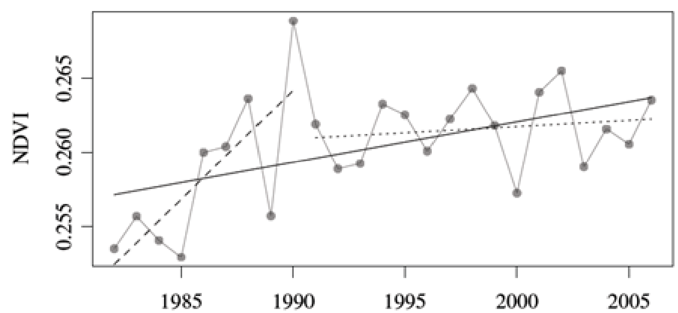


Figure 7.1.2. The trends of the mean NDVI of study area from 1982 to 2006 for the whole China Landmass

A summary of change in vegetation growth dynamic trends associated with land cover and climate across the Asia-Pacific, Asia-Australia and North America regions are shown in Figure 7.1.3. These are based upon satellite observations from 1982-2011. The spatial pattern of changes during this period are displayed for the Asia-Australia region in Figure 7.1.4 and the North America region in Figure 7.1.5. Details can be found in Appendix 7.1.

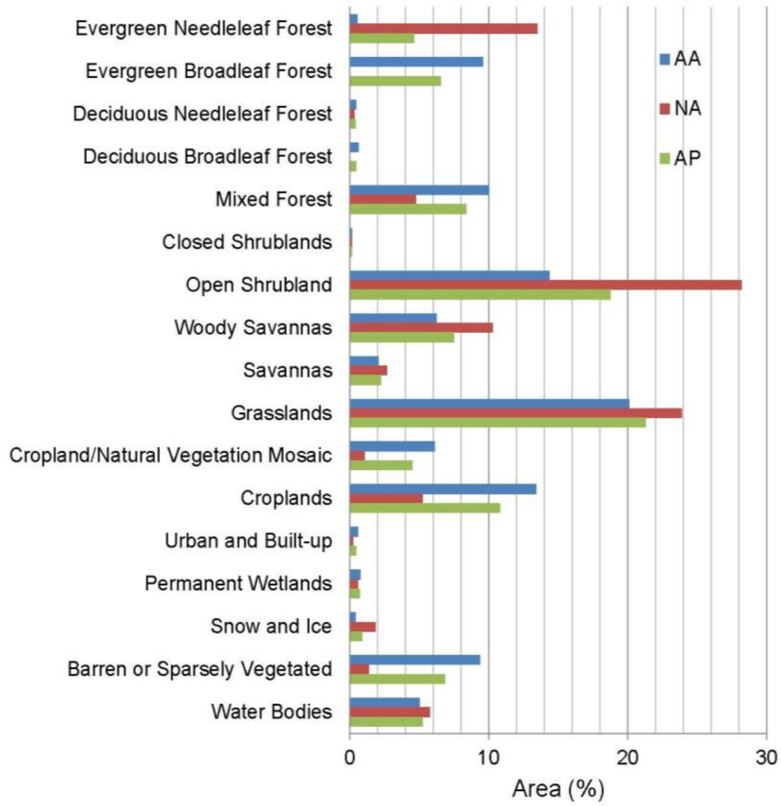


Figure 7.1.3. Histograms of land cover types (% area) for the Asia-Pacific (AP), Asia-Australia (AA) and North America (NA) regions.

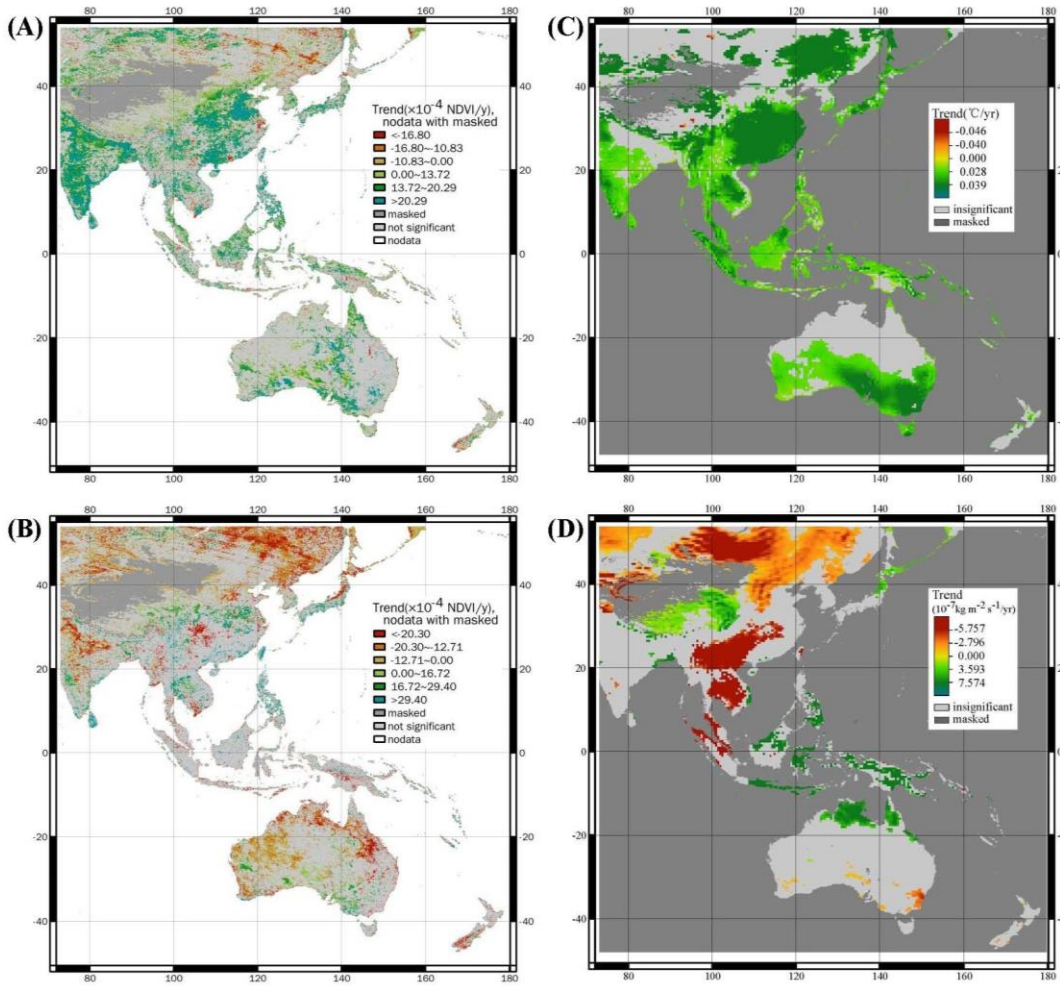


Figure 7.1.4. Spatial distribution of changes in vegetation growth dynamics, air temperature and precipitation in the Asia-Australia (AA) region from 1982 to 2011. (A) Annual productivity (annual mean NDVI); (B) growth seasonality (annual standard deviation of NDVI); (C) annual mean air temperature; and (D) annual total precipitation.

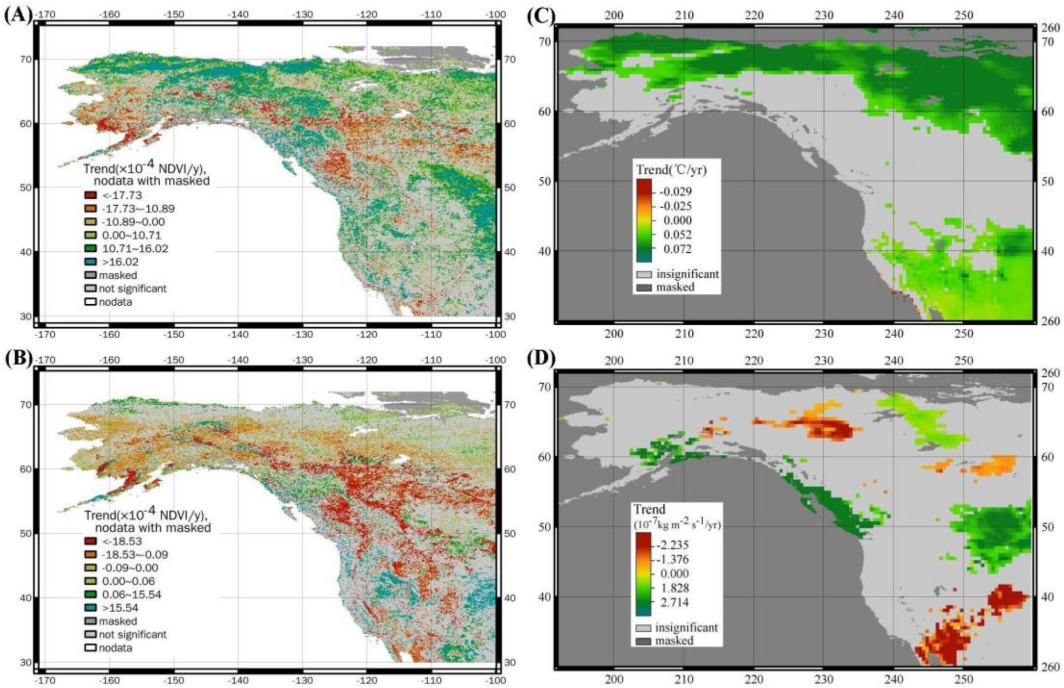


Figure 7.1.5. Spatial distribution of changes in vegetation growth dynamics, air temperature and precipitation in the North America (NA) region from 1982 to 2011. (A) Annual productivity (annual mean NDVI); (B) growth seasonality (annual standard deviation of NDVI); (C) annual mean air temperature; and (D) annual total precipitation.

7.2 Broad Scale Characterization of Site Potential for Chinese Fir under a changing climate

By Yuhao Lu and Nicholas Coops, Department of Forest Resources Management, University of British Columbia

7.2.1 Background

Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook) has been widely planted and utilized for over a thousand years in China. Given its importance and popularity as a major subtropical coniferous species, Chinese fir plays a key role in the environment, timber supply, carbon stocking, and human society. Since 1949 the area of Chinese fir plantations has nearly tripled with an increasing focus on afforestation and reforestation. Based on the national forestry inventory data, approximately 30% of plantations are Chinese fir dominated, covering nearly 9 million hectares. Found mostly in South China, Chinese fir timber accounts for 25% of the national commercial timber production.

Chinese fir is also characterised by its fast growth rate when planted in a monoculture plantation, producing volume up to 450 m^3/ha after 25 years. Fast growing planation can not only sustain the timber supply, but also provide an enormous opportunity for increasing terrestrial carbon stocks, and therefore are suggested as an approach to efficiently mitigate the impacts of global climate change.

China, like other region on Earth, is undergoing climatic changes. Studies have indicated the concern that Chinese fir volume yields and carbon storage may progressively deteriorate over the years under a changing climate, and consequently impact Chinese fir's ecosystem services and timber supply in the future.

7.2.2 Application of physiological modelling for forestry to predict growth and distribution

The mapping of the distribution of Chinese fir under a changing climate has a number of challenges. In this project, we focused on regions in southern China (Figure 7.2.1), and assessed the impact of climate change on Chinese fir by applying a simple process-based model (3-PG) in two phases. Both current and future climate scenarios were generated by ClimateAP across the study area, and modelled for further analysis and comparisons.

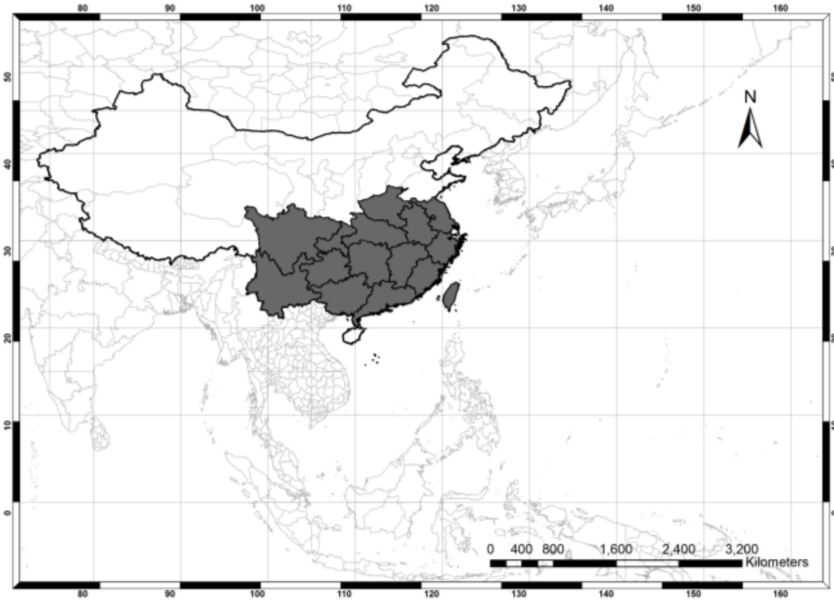


Figure 7.2.1 Provinces covered in this study located in South China.

The 3-PG model (Physiological Principles in Predicting Growth) was used in this study. It is a simplified stand level, single species growth model, applying well-established physiological equations and constants to the species of interest (i.e. Chinese fir). Model inputs include 1) monthly summarized climate data of maximum/minimum temperature, number of frost day, mean precipitation, and solar radiation, 2) parameterized species physiological attributes, and 3) site variables. The 3-PG model, based on these inputs, estimates the climate modifiers from which both the stand productivity and the distribution of Chinese fir can be predicted.

The 3-PG was first run for a 20-year period to reach maximum LAI and canopy closure. Four monthly modifiers were then extracted including the degree that soil water availability, suboptimal temperature, frost, and vapour pressure deficit (VPD) restricted photosynthesis for the four seasons. A decision tree analysis was then undertaken using Chinese fir's presence-only data to determine the potential distribution. As only presence data was available to train the decision tree, pseudo absences were generated using a method adapted from Zaniewski et al., (2002). Random absence points with 30% or less chance of being true absences were removed based on the first run of decision tree analysis. A list of filtered absences was then applied with presences to model species' distribution under a given climate scenario.

To predict the productivity of the species, 3-PG was again run for a period of 20 years. Predictions of stand volume and Net Primary Production (NPP) were then extracted and analysed. The species distribution models generated in the previous phase were then applied as masks to clip model predictions to locations where Chinese fir was predicted to be present. A threshold of 450 m^3/ha was then used to extract and calculate the total area of predicted present sites that have an equal or greater volume than the pre-set threshold value.

7.2.3 Results

The predicted distribution of Chinese fir was shown in Figure 2. Under the current climate scenario (Figure 7.2.2a), the species distribution covers between approximately 21 to 35^{o}N and 101 to 121^{o}E in Mainland China as well as central Taiwan. Modelled distribution under climate scenario A1B and A2 (Figure 7.2.2b-7.2.2c) suggest a likely northward shift with minor changes in the south, resulting an overall increased species distribution. Scenario A1B compared to A2 also indicates that central China is likely to become more suitable for Chinese fir, but with a less profound northward shift.

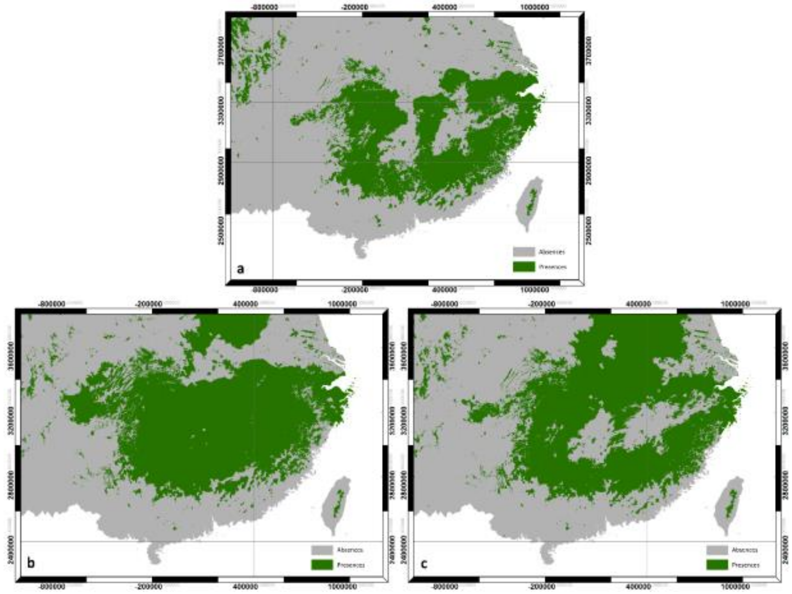


Figure 7.2.2 Graphic representations of modelled Chinese fir distribution under different climate scenarios. a. current; b. A1B; c. A2.

The predicted distribution map masked modelled stand volume of Chinese fir. Results suggest that at age 20 stand volume likely ranges from 150 to 650 m^3/ha (Figure 7.2.3). Based on historical data, we assume that areas with 450 m^3/ha or higher stand volume at age 20 are most suitable for Chinese fir plantations. In total, 4.3 % (~12,000,000 ha) and 3.3 % (~9,000,000 ha) of modelled distributions have a stand volume of more than 450 m^3/ha under scenario A1B and A2, respectively (Figure 7.2.4).

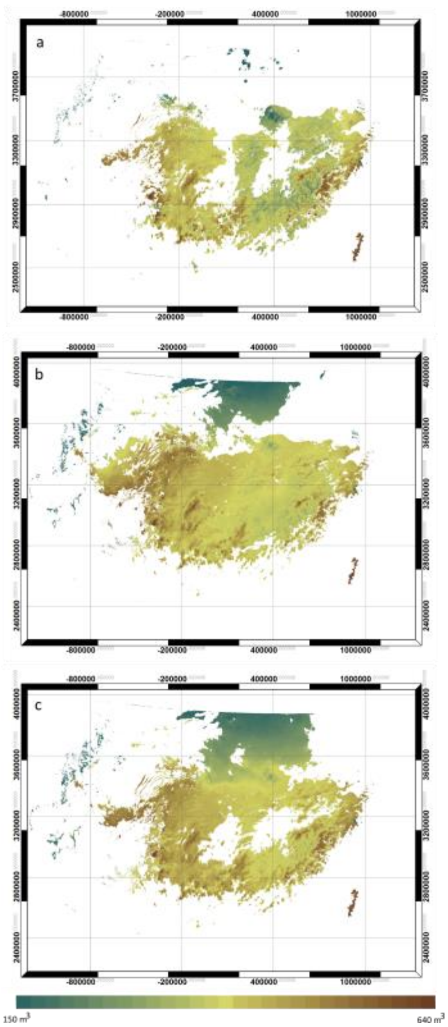


Figure 7.2.3 Volume (m3/ha) at age of 20, predicted by 3-PG. a. current climate; b. A1B; c. A2

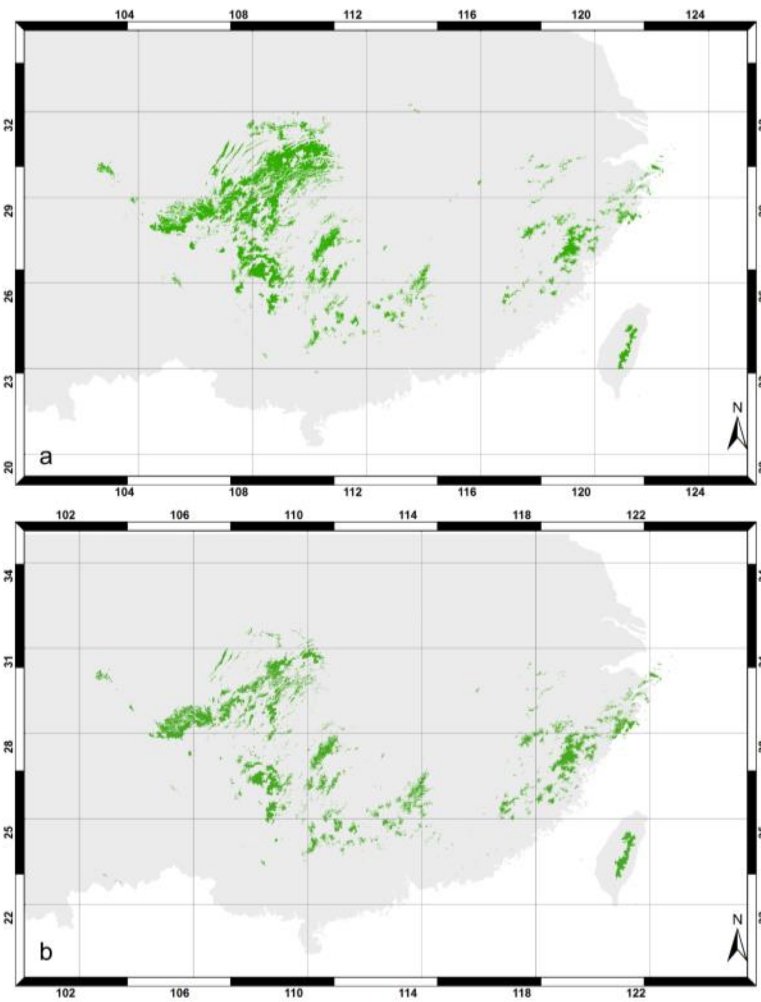


Figure 7.2.4 High productive sites (> 450m3/ha stand volume) within predicted present areas. a. A1B; b. A2.

Net primary production (NPP) was also calculated in this study. Current annual carbon uptake of Chinese fir averages 18 Mg/Dry matter/year, or 930 g carbon /m^2/ year across the study area. Figure 5 shows the percent change between the baseline (current) and two climate scenarios.

Although changes in NPP are more profound in scenario A1B (Figure 7.2.5a), both scenarios indicate a NPP drop in southern China, but an increase (> 50%) in central China.

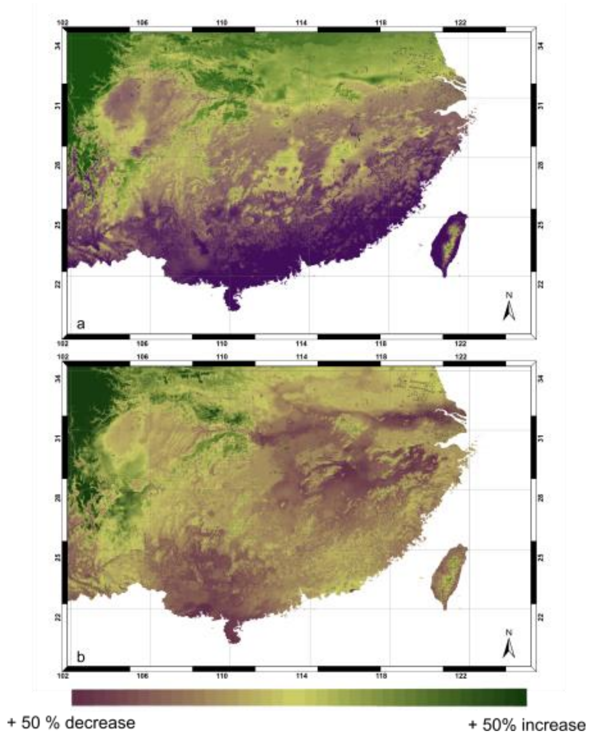


Figure 7.2.5 Percent changes in NPP between baseline and scenario. a. A1B; b. A2.

7.2.4 Discussion

Understanding and quantifying the potential climate impacts on Chinese fir will benefit both forest managers and policy-makers. Chinese fir is considered one of the most important conifer species in China, especially in south China where timber is a major economic driver. Our work indicates that climate change will have a dramatic impact on Chinese fir growth and distribution. Forest managers at a local scale will need to adapt by developing management strategies that are best suited to the future climates. At a provincial or national level, distribution patterns and forest productivity will assist forest policy-makers to generate more accurate and scientific-based policies.

This work has shown the ability of 3-PG model to estimate Chinese fir's productivity and distribution under a changing climate at both spatial and temporal scales. Previously, the model had been applied in the Pacific region of North America. In addition, by comparing the species distribution and NPP change maps to Liu et al. (2014), we believe that the results of this study provide a valid and analytical estimate of Chinese fir productivity, and encourage the model application to other species and with more climate scenarios if possible. Details can be found in Appendix 7.2.

7.3 Detailed Site Characterisation of BC APFNET Study Site Sites

By Yuhao Lu and Nicholas Coops, Department of Forest Resources Management, University of British Columbia

7.3.1 Background on Douglas-fir

Coastal Douglas-fir (*Pseudotsuga menziesii spp*. *menziesii* (Mirb.) Franco) is highly desirable for timber production, and is considered a critically important species in the Pacific Northwest of North America, occurring in some of the most globally productive forest. In British Columbia, Douglas-fir can be found in over 70% of the currently recognized Biogeoclimatic zones. Douglas-fir is usually the pioneer tree species in post-fire forest ecosystem due to its thick barks and shade-tolerance. Douglas-fir normally outcompetes other shade-tolerant species, and therefore yields a faster growth rates. However, Douglas-fir growth is likely to be limited in areas that have warmer and drier normal conditions. Across its distribution range, studies have shown that Douglas-fir productivity is primarily constrained by water availability. With changes in predicted climate within the region likely to result in warmer and longer growing seasons and potentially drier summer conditions, Douglas-fir is a key candidate for on-going research.

7.3.2 Applications of LIDAR and physiological modelling for forestry

Growth and yield of Douglas-fir are also highly site dependent. Before age 50, rich and productive Douglas-fir stands can achieve up to 2.5 times faster annual growth rates than poor stands. Site varieties therefore post challenges to local, stand level forest management while the general stand dynamics of Douglas-fir at a broad scale are well understood. This gives us the opportunity to further study and predict Douglas-fir growth on a site by site basis using process-based, stand level growth models (e.g. 3-PG model), as well as advanced LiDAR remote sensing technology.

For the past two decades, a number of process-based forest growth models have advanced our understanding between forest stands and other external variables, such as seasonal climatic constraints, soil properties, and water capacity. Compared to the conventional growth and yield estimations developed from static field measurement driven logarithm models, process-based modelling approaches like 3-PG offers the capacity to explore the interactions of ecosystem components and the environment, allowing the potential for analysing forest growth under a changing climate. Undertaking this type of analysis using conventional yield tables is difficult.

In addition to process-based representations of forest growth, advances in using remote sensing technology can improve volume estimates from airborne platforms. LiDAR, as an active remote sensing tool, has been used to provide robust forest inventories as of 15 years ago in Europe. Typically, LiDAR data can be processed in two ways - single-tree approach versus area-based approach. Single-tree approach requires high-density, detailed data which can increase the processing time, therefore limiting the applicability of LiDAR. In contrast, area-based approach offers wall-to-wall estimation of forest attributes (i.e. stem volume) at a landscape level with higher efficiency by developing an empirical relationship between LiDAR predictors and plot measurements. LiDAR estimated stand attributes have shown better or at least equal accuracy in a study by White et al. (2014). In this study we used both 3-PG model and LiDAR remote sensing to assess regional stand volume, and the results were then compared to field-based data.

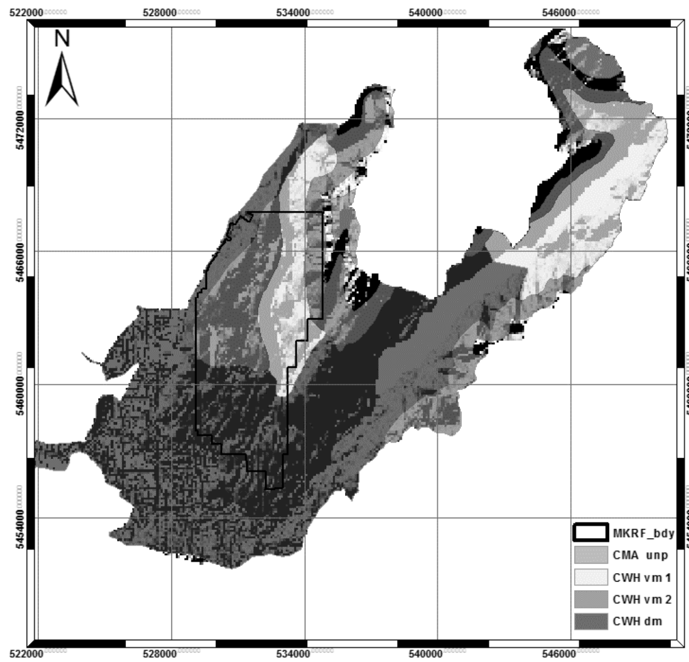


Figure 7.3.1. Study area at MKRF

This study was undertaken at Malcolm Knapp Research Forest (MKRF), one of the University of British Columbia's research sites. The MKRF is 5,157 ha in size, and covers the southwest slopes of Golden Ears Mountains, the east bank of Pitt Lake, and the north edge of Maple Ridge urban area in British Columbia, Canada. The focus of this work is the research forest itself, as well as the wider catchment area in which it is situated (Figure 7.3.1). Douglas-fir is the dominant species in the zone mixed with western hemlock (*Tsuga heterophylla (Raf.) Sarg),* western red cedar (*Thuja plicata* (Donn.)), silver fir (*Abies amabilis* Douglas ex J. Forbes), grand fir (*Abies grandis* (Dougl. ex D. Don) Lindl.), and yellow-cedar (*Chamaecyparis nootkatensis* (D. Don) Spach).

As part of on-going forest inventory procedures within MKRF, a number of plots have been measured to provide estimates of volume and basal area. In 1996, 80 variable radius plots were established within the forest, and their position was verified by either GPS or detailed forest management plans, and a number of plot level forest inventory variables were measured and derived. Of the 80 plots, 19 were dominated by Douglas-fir, the focus of the 3-PG predictions in the paper, and these plots formed the basis of the comparisons with the 3-PG predictions. LiDAR based predictions of volume were based on stand volume of 62 plots (18 plots were removed because of recent harvesting activity or incorrect location information based on management plans).

High-resolution (25 x 25m) climate data input for 3-PG model was generated from ClimateBC, including monthly climatic variables of maximum/minimum temperature, number of forest days, precipitation, and solar radiation. Existing local forest inventory was then used to develop a spatial coverage of establishment date as another model input. Because the majority of the stand was between 1 – 160 years of age, we set the 3-PG initial date to 1850. Model outputs included stand attributes such as volume, DBH, etc., and climatic modifiers of vapour pressure deficit (VPD), temperature, soil water, and frost.

LiDAR data and aerial photography were acquired over the forest in May 2010 through McElhanney Consulting Services Ltd (MCSL) with a point density of 3.1 pulses/m^2, and return points automatically classified into ground and non-ground returns. We used FUSION to process LiDAR point cloud. To achieve the strongest relationship between LiDAR metrics and stand attributes, we varied the ground plot radii from 10 to 60m. Multiple linear regression analyses were executed between all possible combinations of LiDAR metrics and plot volume. Akaike Information Criterion was used to select the most suitable subset of LiDAR metrics to predict the attributes. The best model according to AIC was applied to predict net stem volume across the entire LiDAR coverage.

7.3.3 Results

We found no difficulty matching 3-PG predictions of volume to the field measurement (Figure 7.3.2) with $r^2 = 0.91$ for 19 plots using correlation coefficient with a slope not significantly different from a 1:1 line ($p < 0.05$).

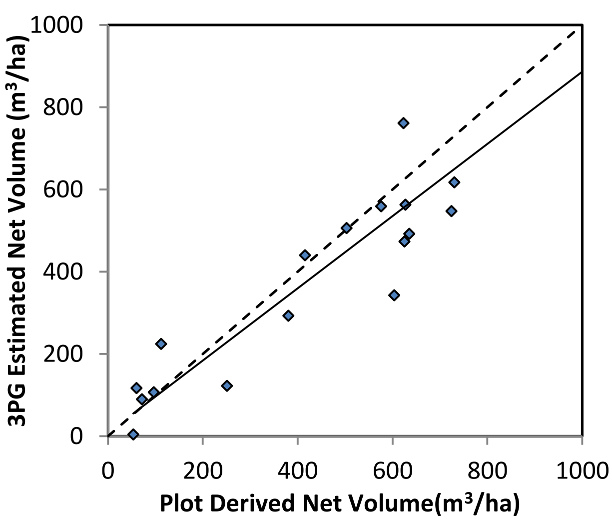


Figure 7.3.2. 3PG Predicted vs observed net stem volume for 19 stands within the MKRF (m^3/ha)

The relationship between LiDAR metrics and stem volume is also clear ($R^2 = 0.70$). A plot radii of 50m gives us the most robust correlation, and the 95th height percentile (HP_{95}) and cover above 2m (C_{2m}) were selected as the best predictors of net volume (see equation below). Our model yielded a bias of 11.7 m^3/ha and an RMSE of 159.6 m^3/ha. Figure 7.3.3 plots the relationship between LiDAR derived volume and field data.

$$\boldsymbol{Volume} = \mathbf{exp}\ [-\mathbf{33.6579} + (\mathbf{2.0058} \times \mathbf{ln}\, \boldsymbol{HP_{95}}) + (\mathbf{7.1162} \times \mathbf{ln}\, \boldsymbol{C_{2m}})] \times \mathbf{1.0872}$$

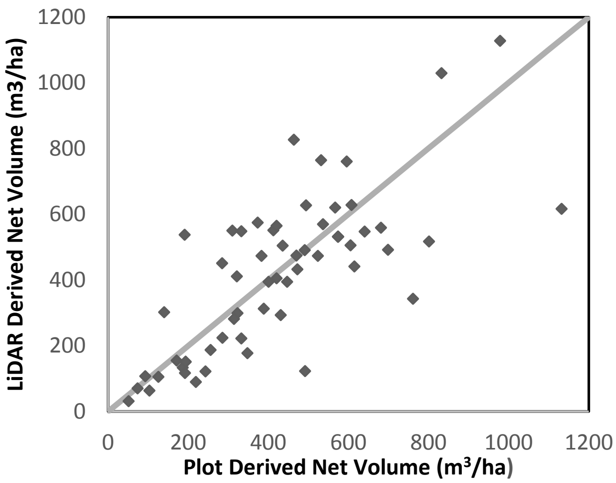


Figure 7.3.3. LiDAR Predicted vs observed net stem volume for 62 stands within the MKRF

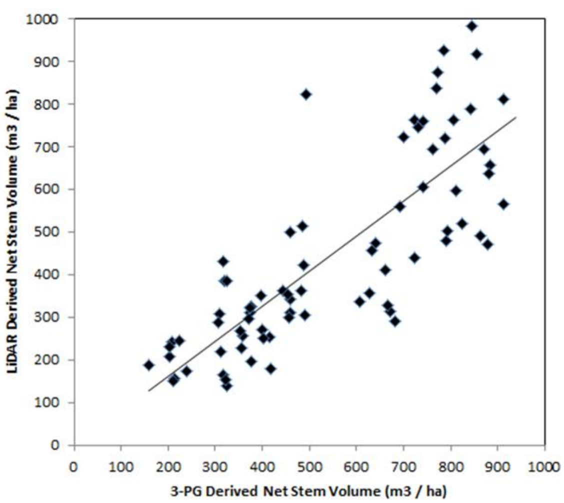


Figure 7.3.4. Comparison between LIDAR derived and 3PG modeled net stem volume for inventory polygons dominated by DF with over 80% canopy cover

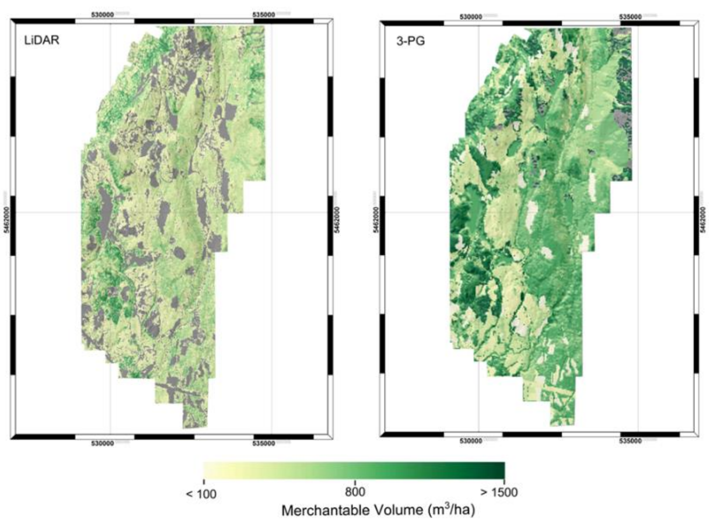


Figure 7.3.5. Spatial predictions of net stem volume in 2008 from (a) LIDAR and (b) 3PG

A comparison of the stem volume as predicted by LiDAR and 3PG is shown in Figure 7.3.4, and shows a strong relationship ($r^2 = 0.65$, $p < 0.01$, N= 77) for inventory polygons that were dominated by Douglas-fir and have canopy closure > 80% as computed from the LIDAR coverage. Figure 7.3.5 displays the spatial predictions of stand volume from LiDAR and the 3-PG model.

7.3.4 Discussion

Empirical growth models and site index tables, which are most often used by foresters, are not well designed to adapt to growth changes under a changing climate, principally as these approaches are derived from past growth, and can only project future growing conditions similar to those in the past. Under a drying climate, 3-PG could be used to simulate future yields, the likely spatial pattern of drought stress, and the benefits of some potential adaptive measurements such as reduced stocking, silvicultural treatment or planting of other more drought tolerant species.

The LiDAR based estimation of stand volume also provided useful predictions, which can complement field-based inventories by providing high spatial resolution sampling of forest structure. LiDAR derived inventories can assist in forest management decisions and planning as well as report on carbon storage and sustainable management practices in managed forests.

There are a number of benefits to utilising both a process based and a LiDAR derived estimate of stand volume. At locations where LiDAR exceeds the 3PG predictions this may indicate an incorrect stand age in the database, the application of some silvicultural treatment such as fertilizer or stand level thinning where a growth response has occurred. In contrast when LIDAR predicts stand volumes less than what is predicted by 3PG this may be indicative of a disturbance, which in this type of forests could be Douglas-fir beetle or other types of defoliators, root rot, or abiotic disturbances such as snow damage or wind throw.

7.4 Climate change and forest fire

By Futao Guo, Guangyu Wang, John Innes, College of Forestry, Fujian Agriculture and Forestry University, China; Department of Forest Resources Management, University of British Columbia

7.4.1 Background

Forest fire is a crucial disturbance factor for a forest ecosystem. The previous studies have shown that climate change has greatly changed the fire regime and frequency in some forest ecosystems, particular in the boreal forest. Understanding the relationship between climate change and forest fire would be a path to identify the response of forests to on-going climate change. On the other hand, a suitable approach (statistic model) is the key to obtain an accurate result reflecting the relationship between climate factors and forest fire properties such as frequency, burned area, spatial patterns etc. Determining the proper models that can be used to identify the relationship between forest fire properties and potential influence factors is the main objective of this sub-program from the APFnet program. Additionally, we analyzed the spatial pattern and driving factors that impacted forest fires in the Chinese boreal forest. The conclusions will benefit forest management agencies by improving their fire prevention planning.

7.4.2 OBJECTIVE 1 – Model selection

It is important to determine suitable models that can reflect the relationship between forest fire occurrence and climate factors in the Chinese boreal forest. In this study, we used six generalized linear models to examine the relationship between the occurrence of lightning-induced forest fires and meteorological factors in the Northern Daxing'an Mountains of China (Figure 7.4.1). The six models included Poisson, Negative Binomial (NB), Zero-Inflated Poisson (ZIP), Zero-Inflated Negative Binomial (ZINB), Poisson Hurdle (PH), and Negative Binomial Hurdle (NBH) models. Goodness-of-fit was compared and tested among the six models using Akaike Information Criterion (AIC), sum of squared errors (SSE), likelihood ratio test (LRT), and Vuong test. The predictive performance of the models was assessed and compared using independent validation data by a data-splitting method.

The ZINB model can be run in SAS 9.2 or higher version or R software etc. The study has proved the advantage of ZINB model in predicting the frequency of fire occurrence over traditional approaches, such as multiple linear regression, Poisson regression, etc. Details are in Appendix 7.4.1.

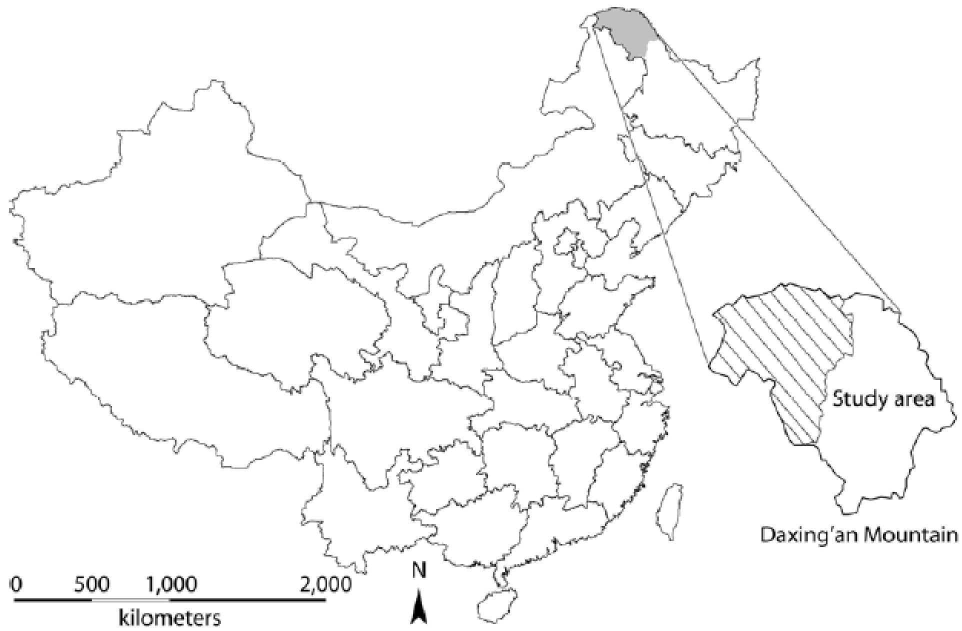


Figure 7.4.1. Study area

7.4.3 OBJECTIVE 2 – Climatic factors affecting burnt area

In addition to fire occurrence frequency, the burnt area is also an important aspect of concern by forest management agencies. The second objective of the study was to identify a suitable model that can reflect the relationship between area burned by forest fire and climate factors in the Chinese boreal forest.

Based on the data structure of burnt area by forest fire, we performed three regression models, including multiple linear regression, log-linear model (log-transformation on both response and predictor variables), and gamma-generalized linear model which was used in other research areas with similar data structure. In our study, the response variables were the burnt area by lightning-caused fire, human-caused fire, and total burned area. The predictor variables were nine climate variables collected from the local weather station. The goodness-of-fit of the models were compared based on model fitting statistics such as R2, AIC, and RMSE.

The results revealed that the gamma-generalized linear model was generally superior to both the multiple linear regression model and log-linear model for fitting the fire data. Furthermore, the best models were selected based on the criteria that the climate variables were statistically significant at $\alpha = 0.05$. The gamma model best indicated that maximum wind speed, precipitation, and days with rainfall greater than 0.1mm had significant impacts on the area burned by the lightning-caused fire, while the mean temperature and minimum relative humidity were the main drivers of the area burned by human activities.

Overall, the total area burned by forest fire was significantly influenced by days with rainfall greater than 0.1mm and minimum relative humidity, indicating that the moisture conditions of forest stands determine the area burned by forest fire. Table 7.4.1 includes the coefficients of predictors that can be used to predict the fire burnt area directly.

The gamma-generalized linear model can be conducted in SAS 9.2 or higher version or R software etc. The study has proved the advantage of gamma-generalized linear model in prediction the burnt area of forest fire over traditional approaches, such as multiple linear regression and log transformed linear regression etc. Details are in Appendix 7.4.2.

Table 7.4.1.Parameter estimates of the gamma best models by different response variables.

Response Variable	Predictor Variable	Coefficien t Estimate	p-value
L-fire	PA	-0.0224	<0.001
	DA	0.2428	<0.001
	MAW	-1.9331	0.003
H-fire	MTE	1.7912	0.035
	DA	-1.9123	<0.001
	MIRH	-0.2171	0.017
T-fire	DA	-0.1337	0.005
	MIRH	-0.5245	<0.0001

Notes: The L-fire, H-fire and T-fire represent the burned area by Lightning-caused fire, the burned area by human-caused fire and the total burned area, respectively. MTE, mean temperature; DA, days that rainfall greater than 0.1mm; MAW, maximum wind speed; MIRH, minimum relative humidity.

7.4.4 OBJECTIVE 3 – Spatial and temporal patterns of historical forest fires

Another component of our research was to determine the spatial and temporal patterns of historical forest fires in the Chinese boreal forest, and analyze the causes of the patterns. As well, we used a prediction model to determine forest fire risk in the Chinese boreal forest, which takes into account several comprehensive factors, including climate variables, terrain, forest types etc.

In this study, K-function and Kernel density estimation were used to analyze the spatial pattern of human-caused fires using S-plus and ArcGIS, respectively. The analysis of driving factors was performed in SPSS 19.0 based on a logistic regression model. The variables used to identify factors that influence fire occurrence included vegetation types, meteorological conditions, socio-economic factors, topography and infrastructure factors, which were extracted through the spatial analysis mode of ArcGIS and collected from official statistics.

The annual number of human-caused fires and the area burnt has declined since 1987 due to the implementation of a forest fire protection act (Figure 7.4.2). There was significant spatial heterogeneity (Figure 7.4.3) and seasonal variations (Figure 7.4.4) in the distribution of human-caused fires in the Daxing'an Mountains. The heterogeneity was caused by elevation, distance to the nearest railway, forest type, and temperature. A logistic regression model was developed to predict the likelihood of human-caused fire occurrence in the Daxing'an Mountains; its global accuracy attained 64.8%. The model was thus comparable to other relevant studies.

These conclusions will help forest management make more efficient fire prevention plans. For example, we identified the fire distribution hotspots in the study area, and the instruments of fire inspection that should be implemented around this area. Additionally, we can also predict the future forest fire risk based on the prediction model. The following figure is the fire risk distribution during fire season of 2015. Details are described in Appendix 7.4.3.

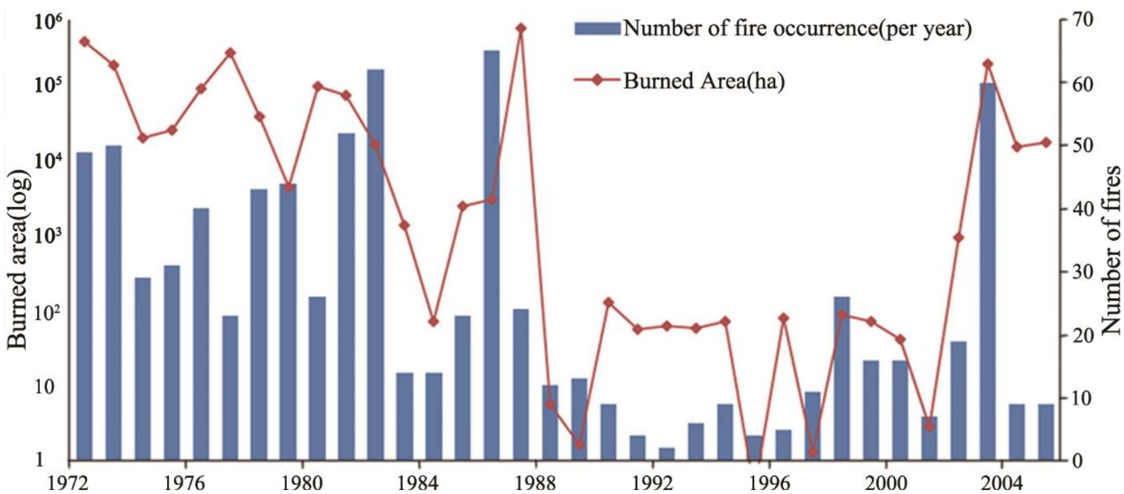


Figure 7.4.2. The annual burnt area and human-caused fire frequency in Daxing'an Mountains during 1972-2005.

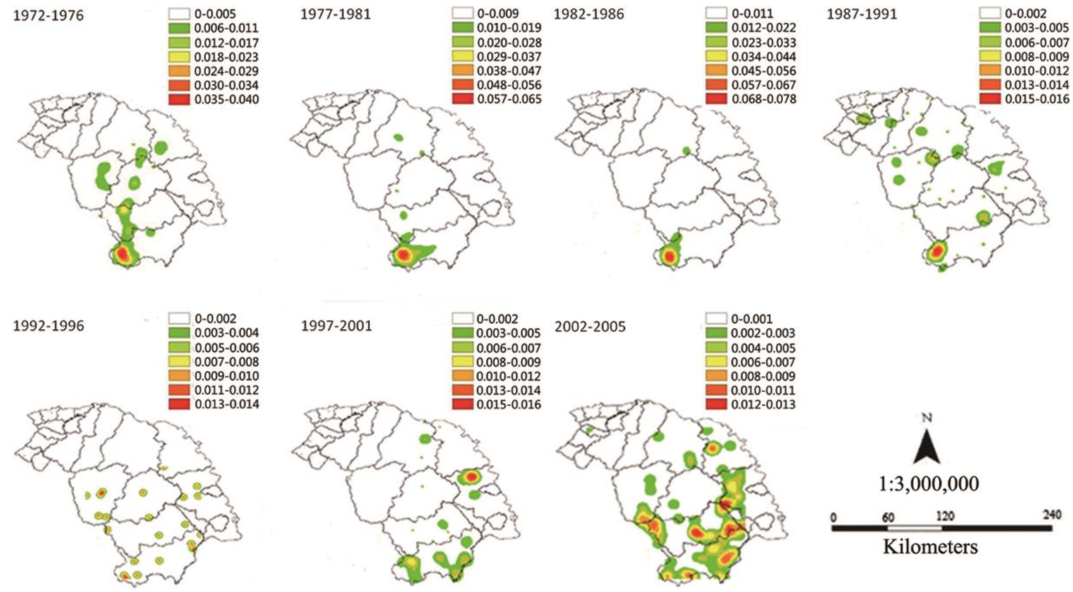


Figure 7.4.3. Spatial intensity of human-caused fires in Daxing'an Mountains during 1972-2005 with five-year time interval. The intensity represented the number of human-caused fire per square kilometer based on 50 km bandwidth scale.

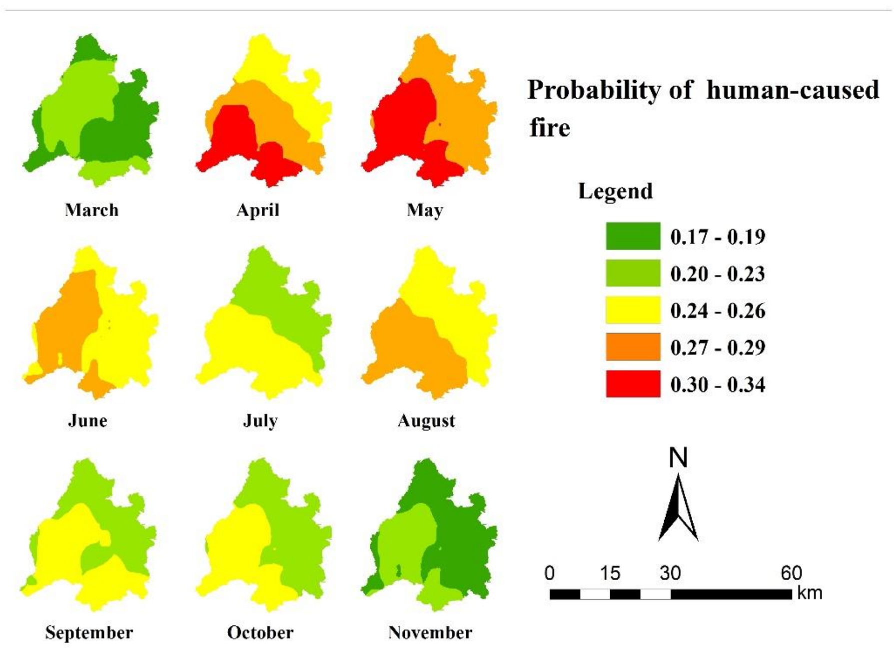


Figure 7.4.4. The human-caused fire risk of Tahe (located in Chinese boreal forest) during the fire season of 2015 based on the prediction model.

7.5 Applications of LiDAR in subtropical forests

By Lin Cao and Nicholas Coops, Nanjing Forestry University, China; Department of Forest Resources Management, University of British Columbia

Remote sensing techniques can provide quantitative spatially explicit information and "wall-to-wall" observations for carbon stock mapping and monitoring. However, since subtropical forests are typically structurally complex and carbon-dense ecosystems, sensors (such as Landsat and shorter waveform RADAR, Radio Detection and Ranging) tend to saturate, which inhibits reliable forest carbon stock estimates in these regions. In addition, optical sensors can only provide limited information of the vertical structure of the forests. Light Detection and Ranging (LiDAR) is an active remote sensing laser technology capable of providing detailed, spatially explicit, three-dimensional information on vegetation structure. A large number of studies have demonstrated the potential of LiDAR to accurately estimate biophysical and structural properties over a wide range of forest types.

This study was conducted at the Yushan pilot site. It is a state-operated forest and national forest park, located near the town of Changshu in Jiangsu province, southeast China (120°42′9.4″ E, 31°40′4.1″ N). The forest covers approximately 1,103 ha, with an elevation range of approximately 20–261 m above sea level. The forest in Yushan belongs to the North-subtropical mixed secondary forest with three main forest types: coniferous-dominated, broad-leaved dominated, and mixed forests.

The objectives of our research work at the Yushan pilot site in this project included: 1) mapping above- and below-ground biomass components in subtropical forests using small-footprint LiDAR components in subtropical forests and 2) using small-footprint discrete and full-waveform airborne LiDAR metrics to estimate total biomass and biomass.

7.5.1 Mapping above- and below-ground biomass components

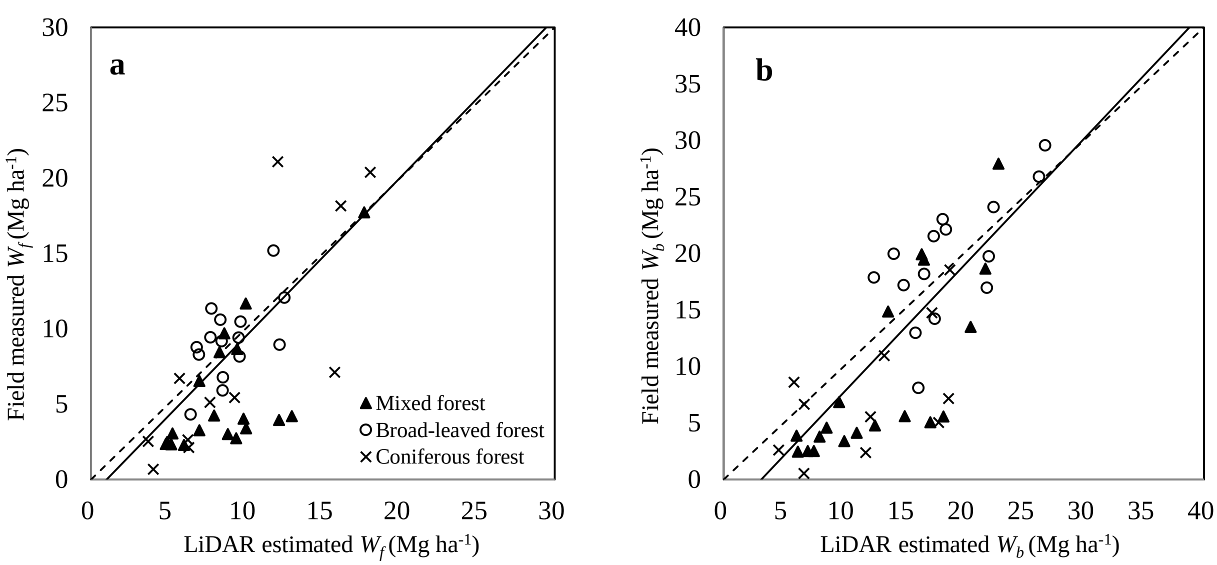
Tropical forests are species-rich, carbon-dense, and highly productive ecosystems, which not only play a significant role in maintaining the regional ecological environment, but also make important contributions to the global carbon balance. Within China, the area of subtropical forests is larger than in any other country, and south-eastern China contains the largest proportion of humid subtropical forests globally. As this area is located in China's most densely populated regions and these regions have the greatest economic growth, their subtropical forests are particularly important for conservation, wood production, and the protection and improvement of the regional environment and carbon cycle. Despite their importance, there is still considerable uncertainty about carbon budgets within these subtropical forests, despite several national-scale studies using historical forest inventory data.

The objectives of this study were: 1) to build models for above- and below-ground biomass components for forest plots (30 × 30 m) in three subtropical forest types (i.e., mixed, broadleaved and coniferous forests) using LiDAR data, and to assess the impact of forest type on the accuracy of the regression models; and 2) to map the above- and below-ground forest biomass components across the site using LiDAR data, and evaluate the accuracy using a suite of independent stand-level field inventory data.

A total of 53 30×30 m (900 m^2) plots were established within the study site, covering a range of species composition, age, and site index, according to a GIS-based historical forest inventory map (2005). These plots were divided into three forest types based on species compositions: 12 coniferous forest plots, all dominated by Masson pine and Chinese fir; 18 broad-leaved forest plots dominated by Sawtooth oak and Chinese sweet gum, and 23 mixed species forest plots with a mixture of coniferous and broad-leaved species were measured for this study. Airborne laser scanner data were acquired on August 17th in 2013 using a Riegl LMS-Q680i flown at 900m above ground level. LIDAR metrics are descriptive structure statistics calculated from the raw LiDAR point cloud.

We found that LIDAR-based biomass predictions fit the stand-based biomass estimates well overall in the 45 reference stands for most of the biomass components with relationships close to the 1:1 line (Figure 7.5.1). The mean value of the individual components for each sample plot, illustrated in Figure 7.5.2, were extrapolated across the entire site using the regression models estimated from the sample plots (Figure 7.5.3).

Overall, small-footprint LiDAR can be used efficiently to estimate the amount of biomass components in subtropical forests. Forest type-specific models represent improved performance over the general model. Results vary between forest types; in this study, the most accurate results were obtained for coniferous stands in homogeneous forest conditions. In addition, some of the canopy height and cover metrics applied (previously used in temperate, boreal and tropical forests) appear to be useful in estimating biomass in subtropical forests such as those in southeastern China. This research illustrates the potential for LiDAR as a technology to assess subtropical forest carbon accurately, and to provide a better understanding of how forest ecosystems function in this region. Details can be found in Appendix 7.5.1.



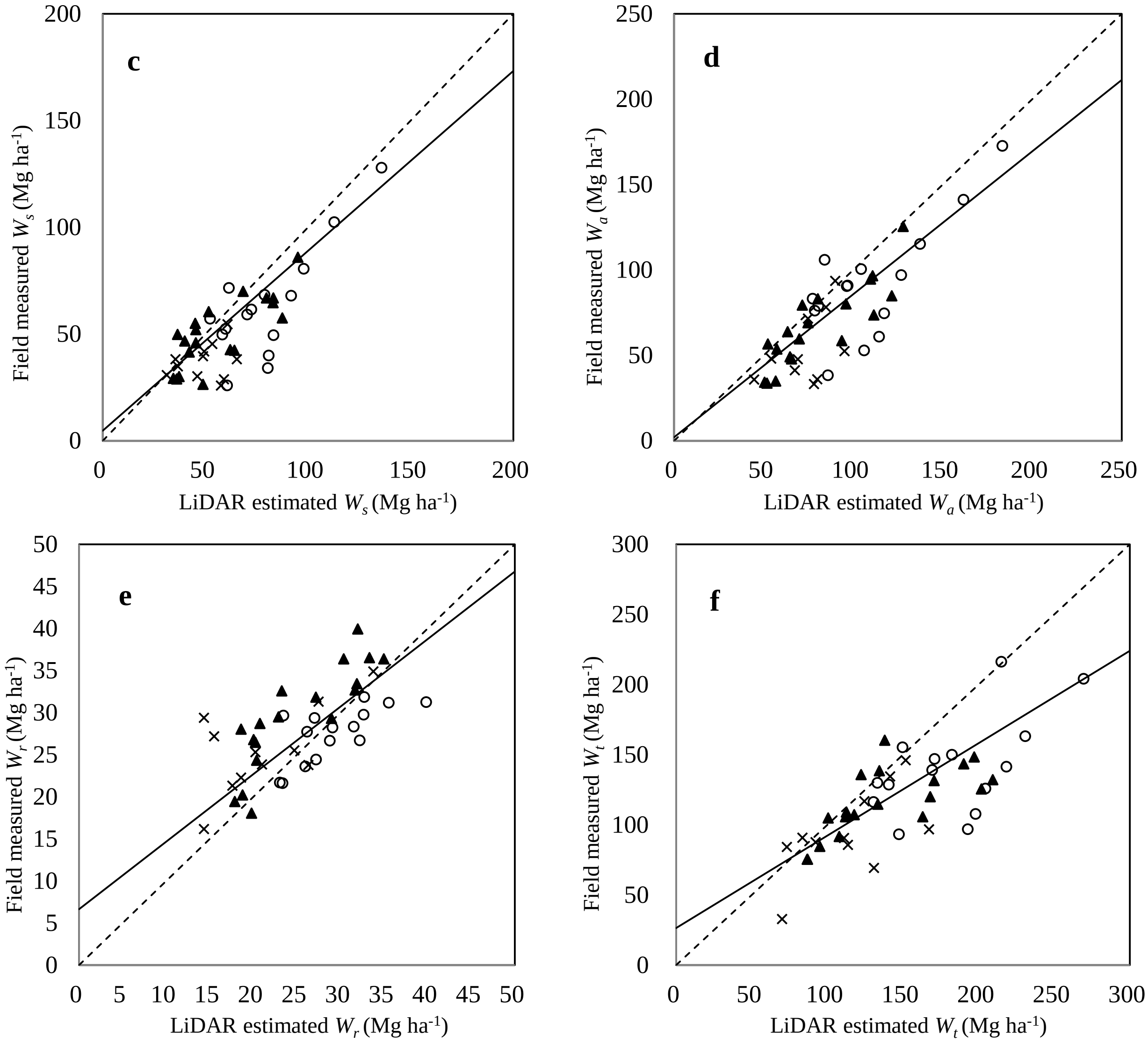


Figure 7.5.1. Scatterplots and 1:1 line (dotted line) of biomass components between the field-measured and the models estimated results of the selected stands (i.e. a. foliage biomass; b. branch biomass; c. stem biomass; d. above-ground biomass; e. root biomass; f. total biomass.). The models were built from the sample plots of three forest types.

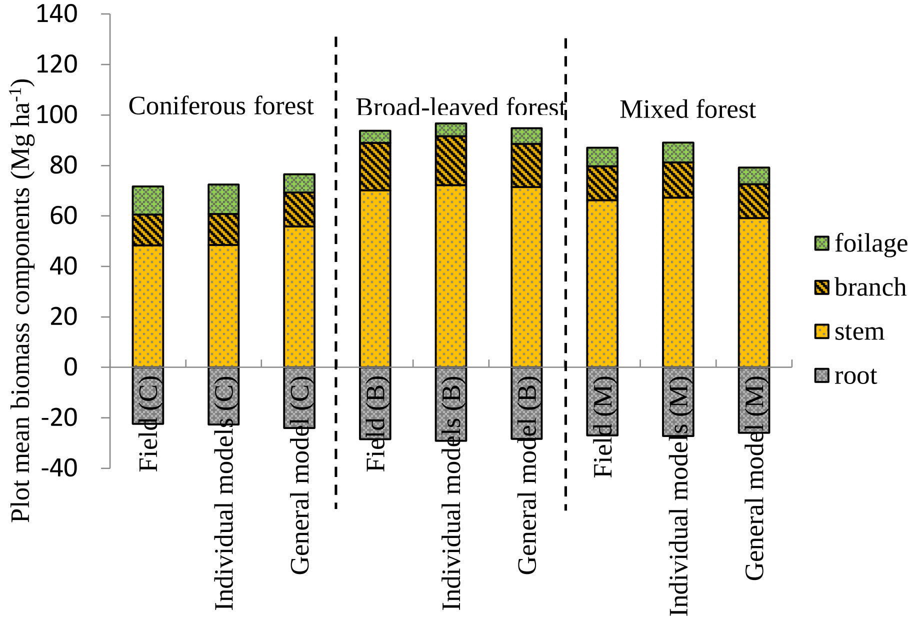


Figure 7.5.2. Mean value of the biomass components (Mg ha^{-1}) of the 53 sample plots from 1) field measurements; 2) estimations of the dummy variable included stepwise regression model; and 3) predictions of the general models of three forest types, i.e., coniferous, broad-leaved and mixed forests.

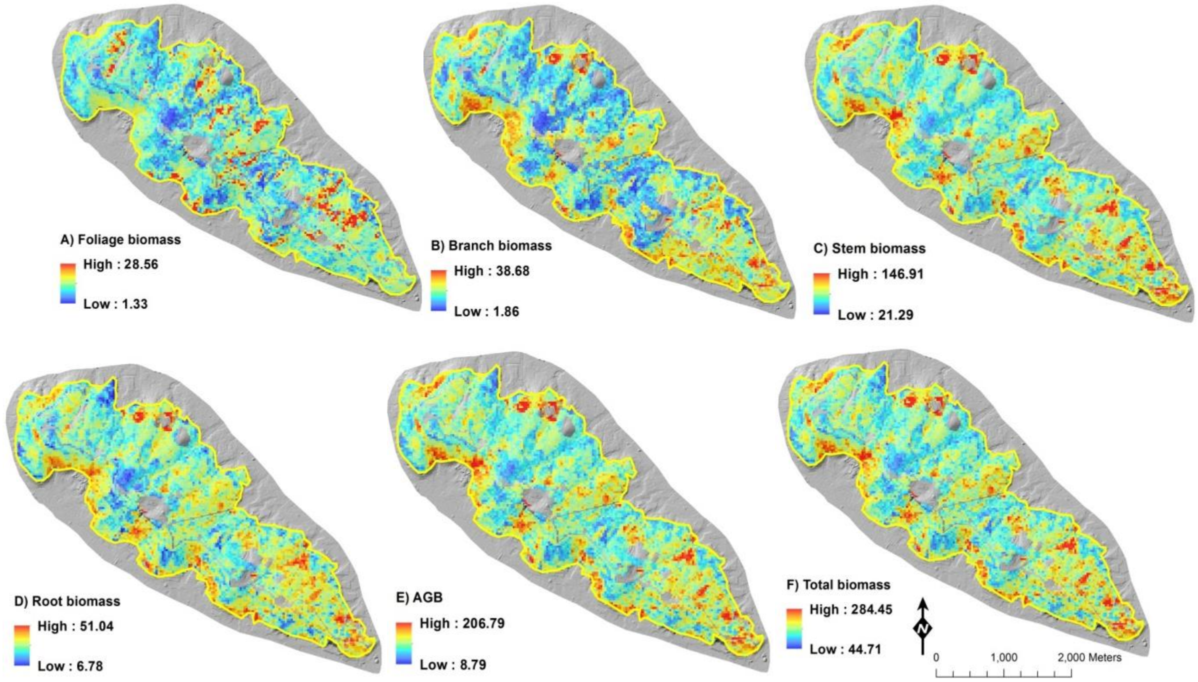


Figure 7.5.3. Maps of biomass components (Mg ha^{-1}) across the research site (pixel size=30m), which calculated from the individual models. a) map of the estimated foliage biomass; b) branch biomass; c) stem biomass; d) root biomass; e) above-ground biomass (AGB); f) total biomass.

7.5.2 Estimating total biomass and biomass Components

As a primary reservoir of carbon dioxide (CO_2) in terrestrial ecosystems, forests play a key role in the global carbon cycle. Globally, forest ecosystems contain approximately 80% of the world's aboveground and 40% of belowground carbon stocks. The subtropical forest biome accounts for approximately a quarter of the area of China, and are particularly important for improving the regional ecological environment and maintaining the global carbon balance. In addition, the partitioned biomass components (i.e., trunk, branch, foliage and root) provide important information for forest management decisions such as the estimation of stem and branch biomass for biofuels calculations, as well as analysing foliage biomass for studying forest growth and assessing crown biomass (i.e., branch and foliage biomass) for predicting fire hazard.

In this research, we examined the relationship between forest biomass (i.e., above-ground and total biomass) and its components (i.e., foliage, branch, trunk and root biomass) with small-footprint discrete (DR) and full-waveform (FW) airborne LiDAR derived metrics in three typical subtropical forest types (i.e., coniferous, broadleaved, and mixed forests). In addition, we examined the estimation capability of DR and FW metric based models for biomass estimation individually and in combination. Finally, the accuracy of the relationships was evaluated within each forest type by comparing biomass estimates with field measurements, which were then used to characterize the environments using additional topographic and vegetation conditions.

Using historical discrete return airborne LiDAR data (2007), a mean height and a cover layer at 30 m cell resolution was developed to be used as an initial stratification of the study area. The height and canopy layers were classified into five equal interval classes in combination with the GIS-based forest inventory data (2012) to guide the selection of ground sample plot. A total of 65 square plots (30 × 30 m) were established within the study site, covering a range of species composition, age classes, and site indices. The LiDAR Data was obtained as described in Section 7.5.1, but used two different techniques focusing on (i) 3-D canopy structural information by discrete (XYZ) LiDAR metrics (DR-metrics), and (ii) the detailed geometric and radiometric information of the returned waveform by full-waveform LiDAR metrics (FW-metrics). This was done to evaluate the capacity of these metrics in predicting biomass and its components in subtropical forest ecosystems.

The results indicated that three sets of predictive models performed well across the different subtropical forest types (Adj-R^2 = 0.42–0.93, excluding foliage biomass) (Figure 7.5.4). Forest type-specific models (Adj-R^2 = 0.18–0.93) were generally more accurate than the general model (Adj-R^2 = 0.07–0.79) with the most accurate results obtained for coniferous stands (Adj-R^2 = 0.50–0.93) (Figure 7.5.5). In addition, LiDAR metrics related to vegetation heights were the strongest predictors of total biomass and its components. This research also illustrates the potential for the synergistic use of DR and FW LiDAR metrics to accurately assess biomass stocks in subtropical forests, which suggests significant potential in research and decision support in sustainable forest management, such as timber harvesting, biofuel characterization, and fire hazard analyses. Details can be found in Appendix 7.5.2.

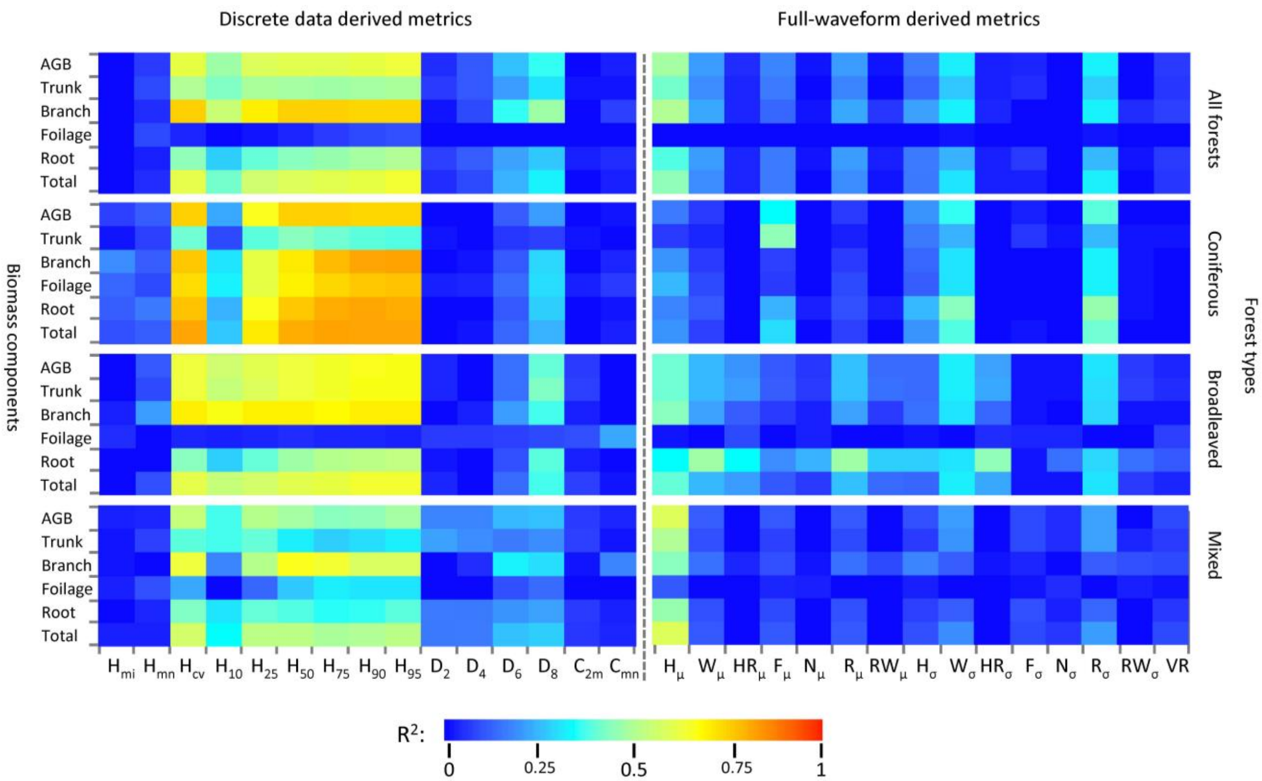
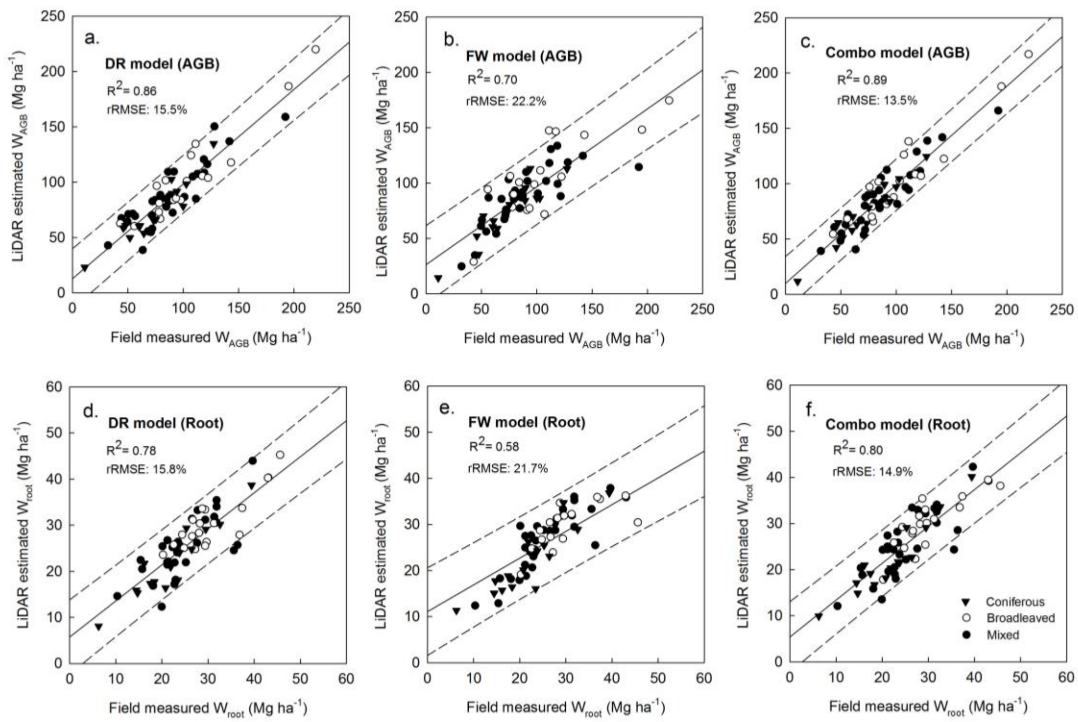


Figure 7.5.4. Intensity graph of the square of the Pearson's correlation coefficient (R^2) between each biomass components and LiDAR-derived metrics. The values of the coefficients are transformed into pixels within a blue-red colour range.



Note: DR model: Discrete data based model; FW model: Full-waveform data based model; Combo model: Model developed from both of DR and FW metrics as a pool of candidate variables; AGB: above-ground biomass.

Figure 7.5.5. Plot-level observed and estimated above-ground and root biomass for the combination of forest-type specific models developed form discrete data based metrics, waveform based metrics and their combinations. (**a**) Above ground biomass (AGB) estimated by discrete data (DR) based model; (**b**) AGB estimated by waveform(FW) based model; (**c**) AGB estimated by combo model; (**d**) Root biomass estimated by DR model; (**e**) Root biomass estimated by FW model; (**f**) Root biomass estimated by Combo model.

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