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REVIEW ARTICLE

Adaptation of Asia-Pacific forests to climate change

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Abstract Climate change is a threat to the stability and productivity of forest ecosystems throughout the Asia-Pacific region. The loss of forests due to climate-induced stress will have extensive adverse impacts on biodiversity and an array of ecosystem services that are essential for the maintenance of local economies and public health. Despite their importance, there is a lack of decision-support tools required to evaluate the potential effects of climate change on Asia-Pacific ecosystems and economies and to aid in the development of regionally appropriate adaptation and mitigation strategies. The project *Adaptation of Asia-Pacific Forests to Climate Change*, summarized herein, aims to address this lack of knowledge and tools and to provide support for regional managers to develop effective policy to increase the adaptive capacity of Asia-Pacific forest ecosystems. This objective has been achieved through the following activities: (1) development of a high-resolution climate downscaling model, ClimateAP, applicable to any location in the region; (2) development of climate niche models to evaluate how climate change might affect the distribution of suitable climatic conditions for regionally important tree species; (3) development and application of forest models to assess alternative management strategies in the context of management objectives and the projected impacts of climate change; (4) evaluation of models to assess forest fire risk and the relationship between forest fire and climate change; (5) development of a technique to assess ecosystem carbon storage using LiDAR; and (6) evaluation of how vegetation dynamics respond to climate change using remote sensing technology. All project outputs were developed with a focus on communication and extension to facilitate the dissemination of results to regional forest resource managers to support the development of effective mitigation and adaptation policy.

Keywords Adaptation · Asia-Pacific · Climate change · Climate model · Ecological model

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Introduction

The Asia-Pacific (AP) region has been identified as exceptionally vulnerable to climate change due to numerous social, economic, and environmental factors (Christensen et al. 2007; Vickers et al. 2010). Climate change is expected to be most detrimental to the least developed and most impoverished nations (Heltberg et al. 2009; Kumar 2012). The AP region contains more than 60 % of the world's population (UNEP 2010), many of whom are dependent on natural resources, such as forests, for their survival. Climate change threatens the vitality and productivity of natural ecosystems, many of which are already vulnerable in the AP due to human activities. With 18.3 %

of global forest cover (FAO 2010), much of the world's biodiversity (CEPF 2014), and the highest number of threatened species (UNEP 2010), loss and degradation of natural ecosystems in the AP region would be detrimental not only to the local communities and economies dependent on these ecosystems, but also to global ecosystem stability, diversity, and socio-economic structure.

Forestry in the Asia-Pacific region

Forest ecosystems are particularly vulnerable to climate change as trees mostly have long generation times and are typically adapted to specific environmental niches, defined by narrow tolerance ranges of temperature, moisture, and nutrient conditions (FAO 2011; Krzyzanowski 2014b; Wang et al. 2015). The distribution of tree and plant species throughout the AP region has developed over thousands of years in accordance with suitable climate niches or bioclimatic envelopes. However, these bioclimatic envelopes are predicted to shift with climate change much more rapidly than forest trees can migrate naturally. As a result, some local forest tree species currently occurring in these ecosystems might not be able to adapt to their local environment in the future. This inability to adapt may compromise the productivity and resilience of these ecosystems, hindering ecosystem function and altering ecosystem dynamics (Innes et al. 2009). Loss or degradation of these ecosystems will not only impact the ecosystems themselves, but might also be catastrophic for the estimated 450 million people in the AP directly dependent on forests for their livelihood, food, and fuel (Krzyzanowski 2014a; RECOFTC 2013; Wang et al. 2015). Understanding the potential impacts of climate change on AP forests is critical for the maintenance of ecosystem health and services, as well as socio-economic, cultural, and traditional benefits to people in the region (ADB 2009).

Globally, forestry and other landuse account for 11 % of CO_2 emissions (IPCC 2014a, b). The AP has some of the highest deforestation rates in the world (FAO 2010), and produces emissions that are considerably higher than the global average (ADB 2009). Furthermore, an increase in forest disturbances due to climate change, such as forest fires and insect outbreaks (Innes et al. 2009), increases the risk of triggering large releases of carbon due to increased tree mortality (Canadell and Raupach 2008), potentially transforming ecosystems from carbon sinks to carbon sources. As such, AP forests are an immense potential contributor to climate change, which is why regional mitigation initiatives are important for meeting local and global emissions reductions targets (Bustamante et al. 2014).

Forest policy and management in the Asia-Pacific

The type and effectiveness of forest governance and climate change policies is highly variable between and within AP economies (Vickers et al. 2010), and their success is often hindered by a lack of good forest governance (FAO 2010; FGLG 2014). Incorporating sustainable forest management (SFM) and adaptive management into forest management practices is a promising way to improve management capacity and ecosystem resilience to climate change. Forests that are sustainably managed are better able to buffer the uncertain impacts of climate change and contribute to climate change mitigation (FAO 2010; Ogden and Innes 2009). Incorporating adaptive management strategies allows forest resource management to continually improve and adapt to changing environmental conditions, policies, or objectives, through regular monitoring, assessment, and reporting of management effectiveness, and allows for flexibility to adjust strategies based on performance evaluation (Innes et al. 2009). Although most economies have included SFM as part of their forest policy (FAO 2010), another key component is the integration of climate change strategies into forest policy and management, but this has yet to be adopted in the AP region (Vickers et al. 2010).

Efforts have been made by several organizations such as the Food and Agriculture Organization (FAO), the Intergovernmental Panel on Climate Change (IPCC), the United Nations Framework Convention on Climate Change (UNFCCC), as well as several nations and research institutions, to develop effective, science-based adaptation and mitigation strategies. The most notable international policy regarding climate change and forestry in the AP is REDD+. REDD+ was developed by the UNFCCC to create a financial value for carbon stored in forests and provide an incentive to reduce deforestation and land degradation (UN-REDD 2009). At a basic level, REDD+ provides financial compensation to forest owners and other involved parties for any financial losses they accrue as a result of foregoing deforestation for development or other forms of land use (FAO 2010; IISD 2013; RECOFTC 2014; UN-REDD 2009). Despite efforts from various organizations, numerous knowledge and policy gaps remain, particularly in regions with low adaptive capacity and limited research and development resources, including much of the AP. For instance, although several AP economies have developed action plans and policies related to REDD+ activities, success has been variable (Paudel et al. 2013; Pham et al. 2012) due to factors such as failure to implement policy, ineffective cross-sectoral coordination, inadequate availability of qualified personnel, and a lack of REDD+ related policies and credible data (Brockhaus et al. 2014; FGLG 2014).

Availability of research and technology

Numerous climate change and ecological models have been developed to improve our understanding of the potential changes and challenges brought on by climate change (e.g. Cao et al. 2014b; Girvetz et al. 2009; Hansen et al. 2013; Kou et al. 2014; Lu et al. 2015; Wang et al. 2015; Zhang et al. 2015). Species distribution models and ecological niche models (ENMs) have been widely used in North America and Europe (Keenan et al. 2011), but their use has been limited in the AP (Kou et al. 2014; (Zhang et al. 2015) due to a lack of tools and research developed specifically for the AP region. These types of models are necessary to understand subtle variations in climate change impacts between regions and ecosystems that cannot be obtained from generalized, large-scale studies and tools. Thus, there is a need for high-resolution models to accurately predict local changes, particularly in parts of the AP where local topography and global climate phenomena, such as El Niño, greatly influence factors such as precipitation and temperature (Christensen et al. 2013).

The development of effective strategies to reduce carbon emissions from forestry activities is dependent upon the acquisition of accurate forest inventory data, such as land-use changes and carbon storage and fluxes (Asner et al. 2010). To achieve this, techniques are needed to accurately measure carbon density and rates of deforestation (Baccini et al. 2012). Multi-sensor satellite data (Baccini et al. 2012) and light detection and ranging (LiDAR) (Asner et al. 2010; Cao et al. 2014b) are tools that can vastly improve the accuracy and spatial resolution of data for variables such as aboveground vegetation carbon density. However, there remains a need for further developments in research, technology, and acquisition of large-scale data sets specific to the AP region in order to reduce forest vulnerability to climate change and improve adaptive capacity.

Overall, there are remarkably few tools and data of sufficient quality pertinent to the AP region that can be incorporated into science-based decision making. This lack of information leads to 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 functioning networks of scientists, stakeholders and policy makers through which scientific knowledge can be applied directly to the decision-making process. Furthermore, dissemination of information needs to be done in a clear, straightforward manner that allows the information to be easily understood and enables resource managers, decision makers, and policy developers to make well-informed decisions (Ogden and Innes 2009).

Research objectives

The overall objective of the project *Adaptation of Asia-Pacific Forests to Climate* Change was to develop tools and modeling frameworks to enhance the capacity of forest communities to adapt to climate change, and to address gaps in research, technology, management strategies and policy within the AP region. For the purposes of this study, the AP region was defined to include all countries within East Asia, South Asia, Southeast Asia, and Oceania, as defined by the FAO (2010), as well as western North America (Fig. 1). Specific objectives included (1) development of a high-resolution climate model to serve as a tool for the entire AP region to facilitate and promote climate change related studies and applications, (2) development of climate niche models for important tree species in the region to provide a method for identifying the most vulnerable species and populations, and formulating adaptive management strategies, and (3) evaluation of the potential long-term impacts of climate change on regional forest growth and development through the application of a spectrum of models to a series of representative pilot sites. The objective of this review paper is to summarize the project achievements, disseminate its results, and review the applicability of models and tools developed within the project to the AP region.

Project outcomes

ClimateAP

Development

Historical climate data are necessary for building models based on relationships between climate variables and plant performance, while future climate projections are essential to predict the impacts of climate change. In both cases, it is desirable to have climate data at high-resolution and high accuracy. The climate model ClimateAP was developed as an extension of the previously developed ClimateBC (Wang et al. 2006) to cover the entire AP region. Development of this model involved data collection, downscaling, and then calculation and derivation of climate variables.

ClimateAP uses the best available 30-year-normal monthly climate data as baseline data for the reference period 1961–1990. Parameter-elevation regressions on independent slopes model (PRISM) monthly data developed by Oregon State University were used when available (China and Mongolia), and monthly climate data from WorldClim (Hijmans et al. 2005) were used for the rest of
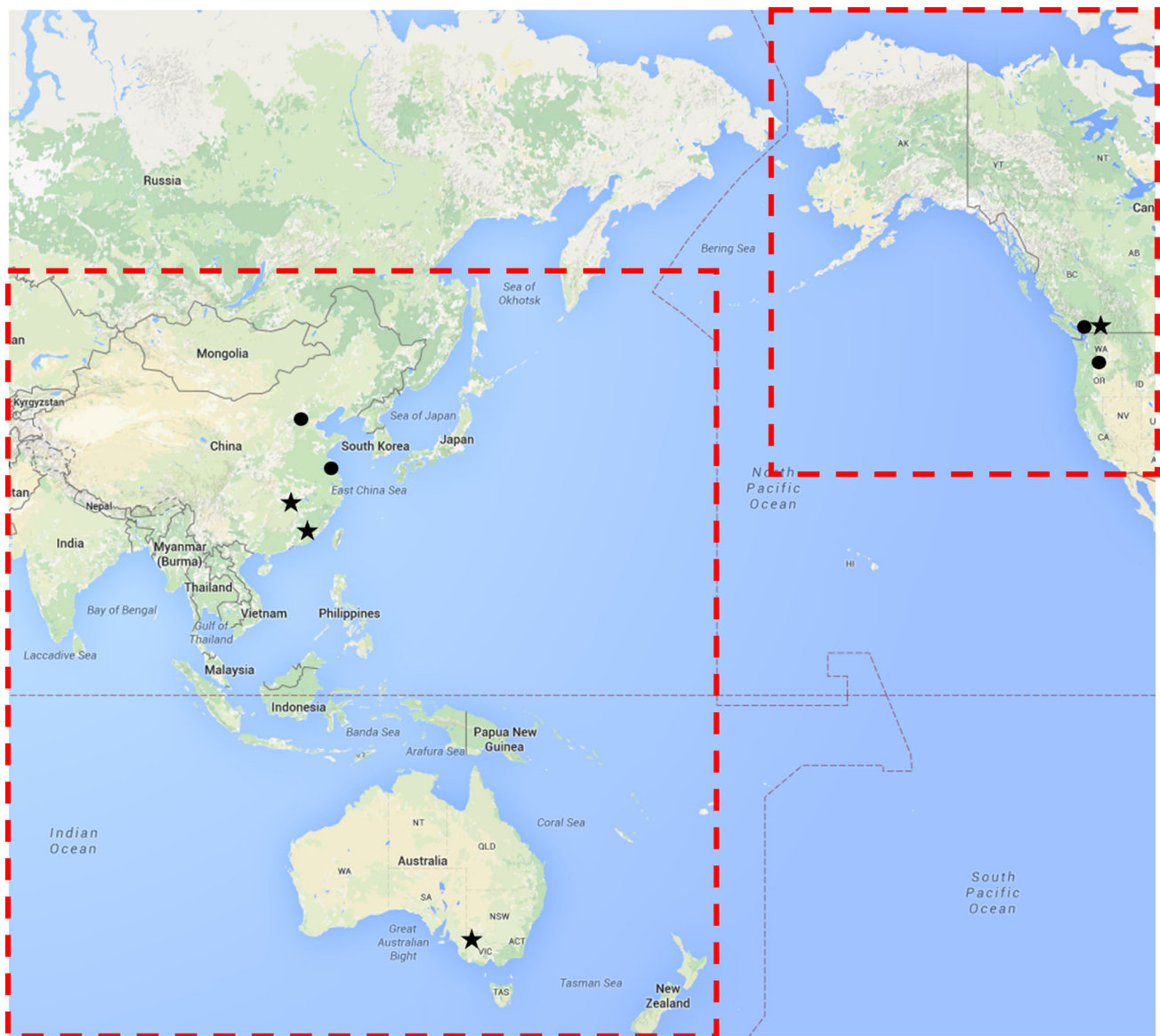
Fig. 1 The study area is highlighted by the *red rectangles*. Pilot experiment sites (*stars*) and partners (*circles*) are also indicated. (Figure adapted from project website: http://asiapacific.forestry.ubc.ca/research-approaches/pilot-site-experiments/). (Color figure online)

the region. Historical climate data were generated by the Climatic Research Unit (CRU) at the University of East Anglia (Mitchell and Jones 2005). The climate data for future periods were from general circulation models (GCMs) from the CMIP5 project in the IPCC Fifth Assessment Report (IPCC 2014b). Two emission scenarios (RCP 4.5 and RCP 8.5) and fifteen GCMs (Taylor et al. 2012) were included.

The baseline data contain 36 primary monthly climate variables including monthly maximum temperatures, monthly minimum temperatures, and monthly precipitation. ClimateAP downscales the gridded data for these variables into scale-free point values using a combination of bilinear interpolation and elevation adjustment (Wang et al. 2006, 2012). ClimateAP also calculates and derives many additional biologically-relevant climate variables from monthly climate variables, such as degree-days, the number of frost-free days, extreme temperatures, and moisture deficit. Many of these variables are normally calculated from daily climate data from weather stations.

The delta downscaling approach described in Wang et al. (2012) was used in the development of ClimateAP to generate point data (scale-free) from historical and future monthly climate data. Using 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 that reflects topography much better than the original data. Because the baseline data generated by ClimateAP are more accurate than the historical and future projections, this process is meant to improve prediction accuracy for both historical and future data. For historical data covering the period 1901–2012, ClimateAP uses historical time series data generated at CRU (Mitchell and Jones 2005). Future climate data were from GCMs of the Climate Model Intercomparison Project 5 (CMIP5) corresponding to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2014a, b). Fifteen GCMs were selected, covering the major clusters of similar Atmosphere–Ocean General Circulation Models AOGCMs) by (Knutti et al. 2013). The model includes two greenhouse gas concentration trajectories or Representative Concentration Pathways (RCP): RCP 4.5 and RCP 8.5 (Taylor et al. 2012).

Outcomes

The interface of the standalone MS Windows desktop version and the coverage of ClimateAP are shown in Fig. 2. The desktop version is freely available at http://asiapacific.forestry.ubc.ca/research-approaches/climate-modeling. The program extracts and downscales the gridded baseline (1961–1990 normal period) monthly data (2.5 × 2.5 arcmin) to scale-free point values, and calculates seasonal and annual climate variables for specific locations based on latitude, longitude and elevation. The desktop version allows users to interactively obtain climate data for a single location at a time. Alternatively, users can obtain climate data for unlimited numbers of locations by feeding an input dataset to the program.

Climate AP also downscales and integrates historical (1901–2012) and future climate datasets for 2020s (2010–2039), 2050s (2040–2069) and 2080s (2070–2099). A time-series of annual projections is also available for the historical years between 1901 and 2012. The output of the program includes both directly calculated and derived climate variables, for a total of 208 climate variables for historical and future periods at specific point locations (Table 1).

A Google Map based version is also available (www.climateap.net) for spatial visualization and easy access to climate data. Users can click on the map to obtain climate data for locations of interest. The output of the climate data can be saved on a local computer.

ClimateAP has improved the accuracy of regional climate modeling, reduced difficulty in accessing climate data, and provided a model applicable to any location in the AP that can be used by anyone, regardless of previous modeling experience. It will serve as an essential tool in climate change-related studies throughout the region, providing a means for the development of more successful
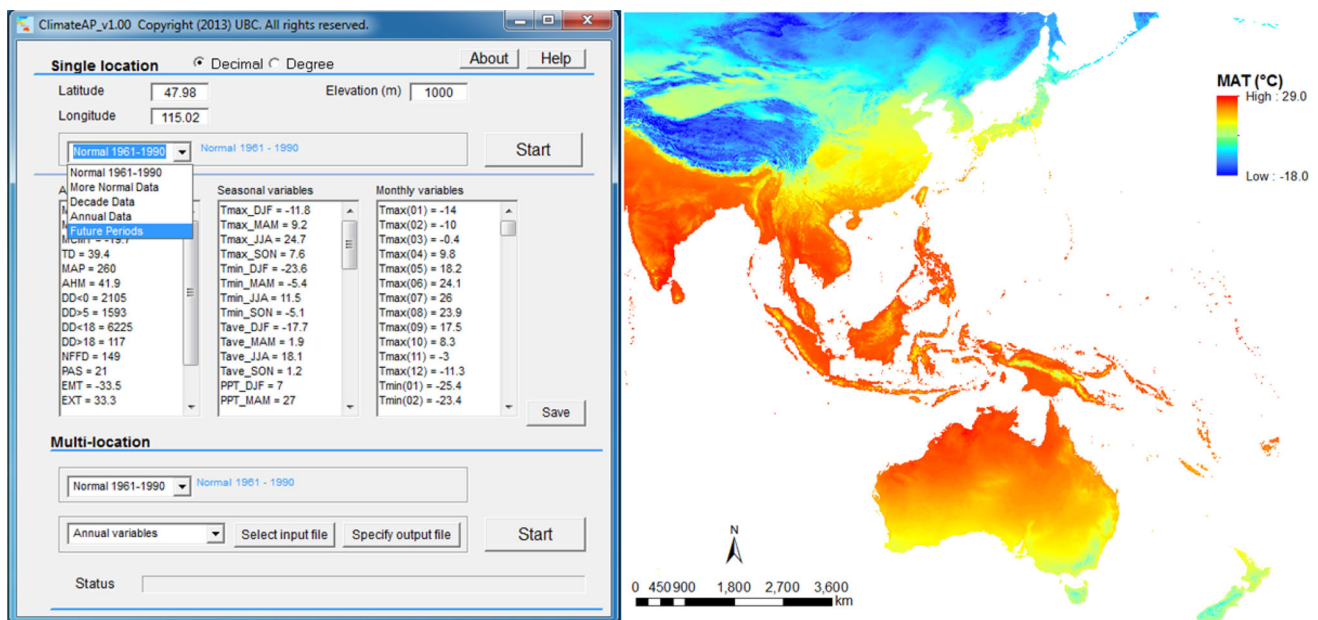
Fig. 2 Interface and coverage of ClimateAP. (Figure adapted from project website: http://asiapacific.forestry.ubc.ca/research-approaches/climate-modeling/)

Table 1 Climate variables directly calculated by ClimateAP

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 (°C)
	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	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 for four seasons (°C)
	PPT_DJF~SON	PPT for 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 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

policy and management plans in all fields, not only forestry. The potential application of ClimateAP to build ecological models and generate useful predictions regarding the impacts of climate change have already been demonstrated in the additional outputs of this project.

Ecological models

Niche-based models

Development

Climate is the primary factor regulating the geographic distribution of forest tree species (Davis and Shaw 2001; McKenny and Pedlar 2003). Reliable, high-resolution climate data (from ClimateAP) can be used in conjunction with ecological models to understand the viability of a species in the area it currently occupies and to project its shift in future periods. Bioclimate envelope models (or ecological niche models) are built based on relationships between the observed presence of a species (or a forest ecosystem) and values of climate variables at those sites. These models were used to predict changes in the climate niche of ecologically and socio-economically important tree species in the AP, including Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook), Masson Pine (*Pinus massoniana*) and Chinese pine (*Pinus tabuliformis* Carr.) in China, Douglas fir (*Pseudotsuga menziesii*) in North America, and Blue Gum (*Eucalyptus globulus*) in Australia (Wang et al. 2016; Kang et al. 2015). However, these tools were developed in such a way that they are applicable to any tree species in any location where the necessary climate and ecological data are available.

ClimateAP was used to generate 66 annual and seasonal climate variables for the reference normal period 1961–1990 for the AP region. Predictions and projections of the geographic distribution of each species were then generated for the reference period (1961–1990 normal) and three future periods (2020s, 2050s and 2080s). This was done for 12 climate change scenarios including six GCMs from the IPCC Fifth Assessment Report (AR5) (ACCESS1-3, BCC-CSM1, CanESM2, CNRM-CM5, CSIRO-Mk3-6-0, and HadGEM2-ES) (http://cmip-pcmdi.llnl.gov/cmip5/availability.html) and 2 emission scenarios (RCP4.5 and RCP8.5) (Taylor et al. 2012). The models were used to generate spatial predictions for each prediction or projection period for each species of interest, and outputs were imported into ArcGIS (v10.2.1) to generate maps. A more detailed explanation of data collection, application, and statistical analysis can be found in Wang et al. (2015a) and Kang et al. (2015).

Outcomes

The application of this type of model generates maps that illustrate the current and projected distribution of the tree species of interest for three time periods (2020s, 2050s, 2080s), and provides clear visuals of the projected changes in species distribution. The model generates several projected distributions for each species in order to generate an ensemble of model predictions to ensure robust analysis. The overall accuracy of these projections is high, with an overall accuracy of >90 % for the five species investigated during this project.

The development and application of this model allows for the assessment of climate change impacts on key species and development of adaptive strategies in forest resource management under a changing climate. A striking finding of this study is the impact of climate change on the shift in the climatic niche for Chinese fir (Wang et al. 2016). Instead of a northward shift, which is normally the case for most of the tree species in the northern hemisphere, the climatic niche of this species is projected to contract at a large scale (Fig. 3). Chinese fir is the most important tree species in China in terms of ecological and economic values. Substantial contraction of its climatic niche in projected future climates may serve as a serious early warning. For further results from the application of niche-based models see Wang et al. (2016).

Process-based models

Process-based models play an important role in evaluating the impacts of climate change on forest stand level productivity, water balance, and carbon storage. Various process-based models were used in this project, including 3-PG, FORECAST Climate, TACA and LANDIS-II, and were applied to various tree species in different locations in order to analyze these processes, while accounting for the unique local physical and ecological requirements.

3-PG

Development

Physiological Principles to Predict Growth (3-PG) is a stand-level growth model that analyzes the biophysical and bio-physiological interactions influencing the stand dynamics of a given species to assess the impacts of climate change on habitat loss. It is a simplified stand-level, single-species growth model that applies well-established physiological equations and constants to the species of interest (Landsberg and Waring 1997; Coops et al. 2010). Model inputs include (1) monthly summarized climate data obtained from ClimateAP, (2) parameterized species physiological attributes, and (3) site variables (Lu et al. 2014, 2015). Based on these inputs, 3-PG estimates climate modifiers from which the stand productivity and distribution of a tree species can be predicted.

The 3-PG model determines the extent that various abiotic variables influence the photosynthesis and growth
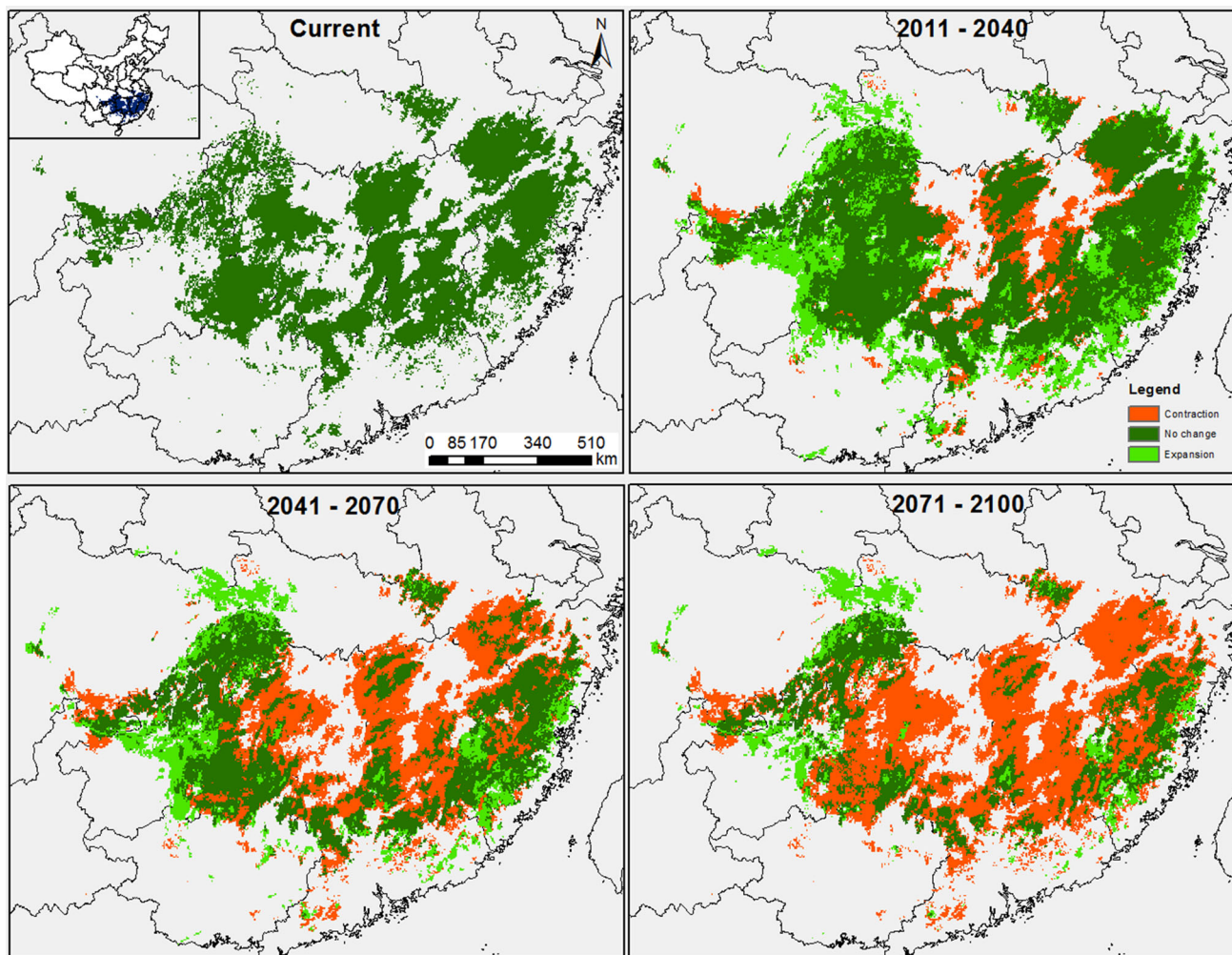
Fig. 3 Future projections of climatic niche for Chinese fir (adapted from Wang et al. 2016)

of a tree species, and uses these variables in a decision tree model to provide the basis for predicting the presence and absence of a species under various climate change scenarios (Lu et al. 2015). To predict the productivity of a species, predictions of stand volume and net primary productivity (NPP) are extracted from 3-PG and analyzed. Unlike other simplified models examining carbon stock and tree biomass, 3-PG differentiates between carbon storage locations such as stems, foliage, and roots (Lu et al. 2015).

Outcomes

3-PG was applied to various species in different locations including Lodgepole pine (*Pinus contorta*) and Douglas-fir (*Pseudotsuga menziesii*) in western North America (Coops et al. 2009; Coops et al. 2011; Lu et al. 2014), and Chinese fir (*Cunninghamia lanceolata*) in southern China (Lu et al. 2015). 3-PG was also used in conjunction with light

detection and ranging data (LiDAR), a remote sensing technology, to evaluate the benefits and downsides of each approach. Using a combination of these tools further enhanced the ability of the analysis to predict stand volume and assess the constraints imposed by climate change on tree species growth (Lu et al. 2014).

There are several benefits to using both process-based and LiDAR derived estimates of stand volume. Process-based growth models provide an effective way to investigate the potential impacts of climate change on the forest estate within a quantitative framework. LiDAR-based predictions of stand volume provide high spatial resolution sampling of forest structure that can complement field-based volume inventories.

Although 3-PG is simplistic in its application, it is robust in its analysis, making this type of modeling more accessible to local forest managers than other, more complex, models of a similar nature. The 3-PG estimates provide additional information to forest managers, as the tools

most often used by foresters (empirical growth models and site index tables) are not designed to adapt to growth changes under a changing climate. Understanding and quantifying altered distribution patterns and forest productivity due to climate change is beneficial at different levels of decision making and management planning. Locally, it will aid forest managers in developing more successful management strategies that are best suited to the future climate, especially those managers working with plantation species. At the provincial or national level, it will assist policy makers in generating more accurate and science-based policies regarding forest ecosystems under a changing climate.

Forecast climate

Development

FORECAST Climate (Seely et al. 2015) was developed through the dynamic linkage of the hybrid forest growth model FORECAST (Kimmins et al. 1999) with the stand-level hydrology model ForWaDy (Seely et al. 1997). This model is able to represent the impacts of climate change on forest growth dynamics. It includes detailed representations of the relationship between temperature and water stress on growth rate, as well as the effect of temperature and moisture content on decomposition and nutrient cycling (Kang 2015).

In this project, FORECAST Climate was calibrated for Douglas-fir (*Pseudotsuga menziesii*), Western red cedar (*Thuja plicata*) and Western hemlock (*Tsuga heterophylla*) at the Malcolm Knapp Research Forest (MKRF) pilot site in British Columbia, Canada. To explore the potential impacts of climate change on the growth and development of this forest, climate change projections were taken from two IPCC AR5 GMCs, with outputs generated for 2020, 2050, and 2080. Through the application of these models, projections were made of the impacts of climate on tree growth, ecosystem development and mortality rates. Annual merchantable volume production was also determined based on the expected growth rate. Additionally, this model projects decomposition rates and nutrient cycling under climate change in order to further understand how these environmental factors will influence the productivity of the ecosystem.

FORECAST Climate was also applied, in conjunction with ClimateAP and climate niche-models, to Chinese fir in Fujian Province, China. The objectives of this application were to evaluate the impacts of climate change on Chinese fir's long-term growth and development and on the spatial distribution of its suitable habitat. Details and results of this analysis can be found in Kang (2015).

Outcomes

The application of FORECAST Climate at MKRF 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. 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 any losses due to mortality.

FORECAST Climate and tradeoff analysis

Stand attribute data generated by FORECAST Climate were also used in conjunction with the landscape summary tool (LST) to perform a tradeoff analysis of alternative management scenarios on the flow of economic wood fiber and specific ecosystem services under different climate change scenarios in Fujian (Kang 2015). LST, a landscape-scale model, was designed in Microsoft Excel to calculate indicators of ecosystem services. It divides the whole project area into discrete analysis units and projects the development of indicators in those units. Specific stand-level data are modeled based on the simulated age of each polygon within the landscape. The nature of the linkage between FORECAST Climate and the LST model is shown in Fig. 4.

Eight indicators were selected to perform the trade-off analysis, 2 for economic production (volume harvested and biomass harvested), and another 6 for non-economic services, with values based on the stand attribute database derived from FORECAST Climate. Twenty-seven alternative management and climate scenarios were developed using a factorial analysis approach (3 rotation length scenarios * 3 harvest retention options * 3 climate scenarios) and explored over a 50-year time period (Fig. 5). Indicators were expressed as relative values (scaled from 0 to 1) to facilitate direct comparison among indicators, and a variable weighting decision approach was included to allow users to determine the importance of each indicator. A total score based on a weighted sum of the indicators was calculated for each scenario to allow for a ranking of management options, and a decision matrix output table was produced to illustrate the trade-off analysis results.

LST can be applied to any species in any location. It provides a straightforward framework for managers and decision-makers to quantify the combined benefits and tradeoffs of multiple, potentially conflicting, objectives, and enables the development of the best possible management strategy to achieve specific objectives under a
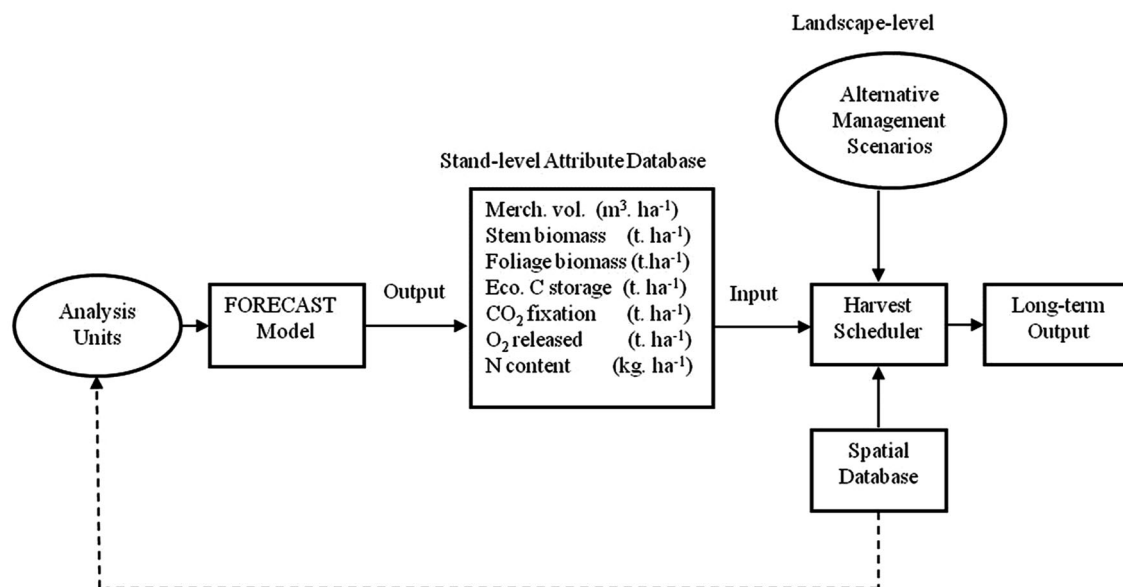
Fig. 4 A schematic diagram illustrating the relationships and data transfer pathways between the FORECAST Climate and LST models (Figure adapted from Kang 2015)
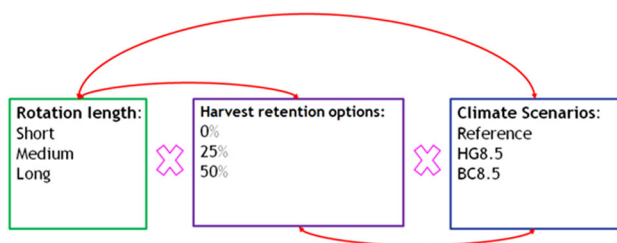
Fig. 5 Combinations of rotation length, harvest retention and climate scenarios

changing climate. For full details of this process, see Kang (2015).

As a whole, FORECAST Climate provides a framework to assess climate change impacts, which can lead to improved adaptation strategies in SFM and species selection. When integrated with LST, it provides an effective decision-support tool for forest managers and allows for the efficient evaluation of the trade-offs between management designed to optimize economic returns versus management designed to maximize the flow of non-commercial ecosystem values. Furthermore, FORECAST Climate and LST can be applied to any location and species of interest, provided the necessary data are available, and should be explored further to increase understanding of the impacts of climate change on key tree species. It is important to note that these model projections do not account for the impacts of climate change on biotic and abiotic disturbances, such as insects and fire, which may influence the realized future ecosystem productivity (Kang 2015). Further work should be carried out to explore the potential influence of such events.

TACA and LANDIS-II

Development

TACA is a mechanistic species distribution model (Nitschke and Innes 2008) that facilitates 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. TACA-GEM (Germination and Establishment) was developed to model the suitability of a site for species regeneration and survival (Nitschke and Innes 2008; Nitschke et al. 2012). TACA-GAP (growth and productivity) is a combination of the TACA-GEM (Nitschke et al. 2012) and BRIND models (Shugart and Noble 1981) used to estimate annual net primary productivity and maximum biomass that a species can achieve on a site given climate and soil parameters. LANDIS-II 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, TACA-GAP, and LANDIS-II were applied to the Central Highlands Region (CHR) study area in Victoria, Australia to examine the spatial impacts of climate change on tree species with respect to suitable areas for regeneration and productivity. The impacts of management, fire, and climate change on the growth stage distribution were also examined. Modelling was conducted for 32 *Eucalyptus* species, focusing on *Eucalyptus regnans,* as it is the most sought after species for timber production

in the region and plays a key role in water production, carbon stocks, and habitat for native wildlife.

TACA-GEM and TACA-GAP were used to model the suitability of a site for species regeneration and survival and to estimate the annual net primary productivity and maximum biomass that a species could achieve on a given site under different climate scenarios. TACA-GEM was used to provide the regeneration parameters and TACA-GAP the productivity parameters for LANDIS-II under historic and future climate scenarios. LANDIS-II was then used to simulate ecological processes such as succession, seed dispersal, disturbance, and climate change. Climate data from ClimateAP was used to select climate inputs for all three models.

Outcomes

Results of the application of TACA models and LANDIS-II to the CHR pilot site are illustrated in Fig. 6. *E. regnans* was modeled 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 suggests that regeneration may become more limiting than growth under climate change. Landscape modelling suggests that the impacts of climate change on *E. regnans* forests could result in a 48.2 % (±2.1 %) decline in species distribution compared

to a 6.7 % (±1.9 %) decline that may occur without climate change over a 200 year period. Figure 7 summarizes the spatial impact of climate change on this species, identifies areas in the landscape where *E. regnans* remains resilient to climate change, and also illustrates the impacts of management, fire, and climate change on the growth stage distribution. Since many of the resilient areas are located in protected areas, the effect of management is negligible, though a recruitment bottleneck is evident under climate change.

A tradeoff analysis between alternative management scenarios was conducted using these models to test the interaction among management, climate change, and ecosystem services. This analysis was used to measure how key ecological and economic services, such as mammal habitat and timber supply, perform under different management strategies and different climate scenarios. For the application at CHR, no management strategy was able to maintain all ecosystem services at full capacity. However, depending on the management objective, it was clear that some strategies would outperform others. This type of information is important to improve management decision making so that strategies can be targeted to achieve the management objectives deemed most important for that region or ecosystem.

Integration of these models enables assessment of the spatial impacts of climate change on a tree species with

Fig. 6 Regeneration (**a**, **c**) and productivity (**b**, **d**) results for *E. regnans* under historic (**a**, **b**) and 2080 s climate change (**c**, **d**). *Red* to *green* indicates increasing suitability for growth and regeneration. A maximum regeneration score is 1.0 and maximum productivity is 1250 tonnes of biomass per hectare. (Color figure online)
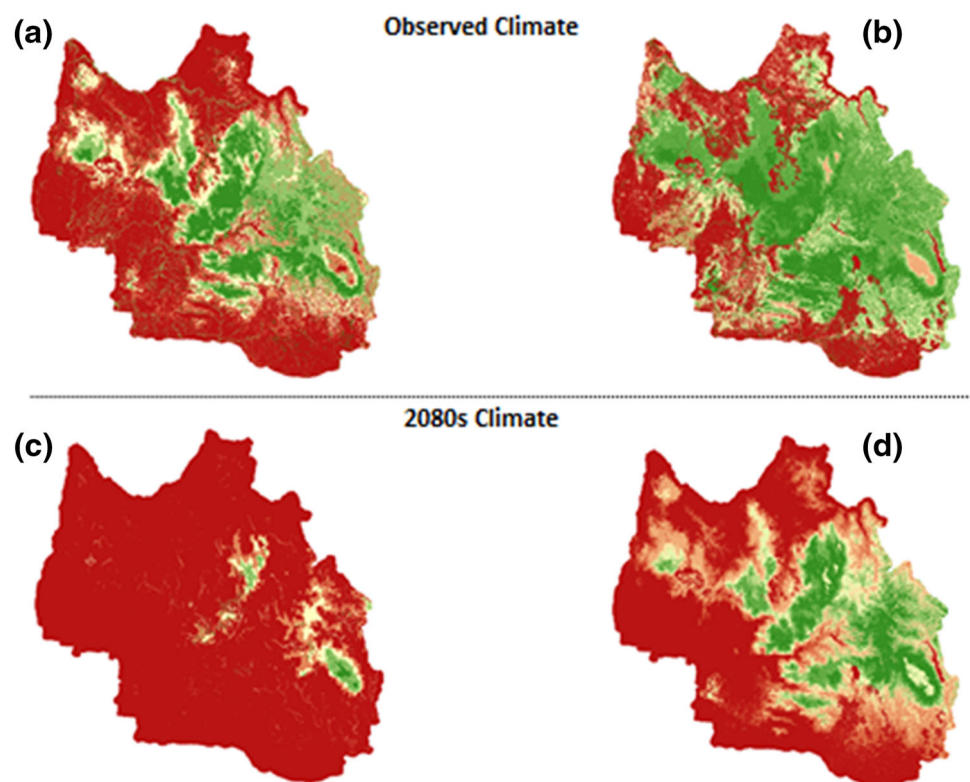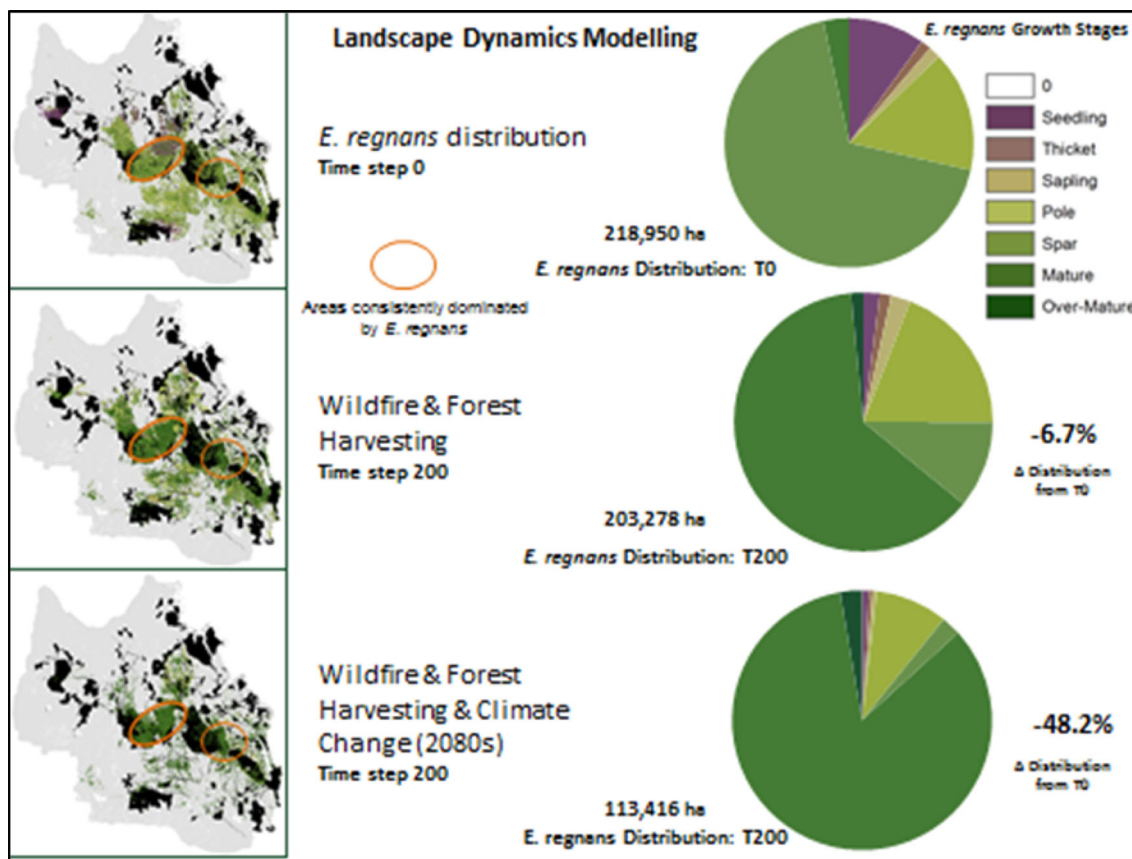
Fig. 7 Landscape distribution and dynamics of *E. regnans* under a factorial of management and climate change. A recruitment bottleneck is evident in the bottom chart and *orange circled areas* indicate areas of potential resilience. *Black areas* indicate protected areas (parks or special protection zones). (Color figure online)

respect to suitable areas for regeneration and productivity, as well as the impacts of management, fire, and climate change on the growth stage distribution. The impact of climate change on ecosystem services, such as harvestable timber and amount of habitat available for native species, can also be considered. Modeling the interaction between management, climate change, and ecosystem services, and performing trade-off analyses under difference management scenarios, is highly beneficial for forest managers when developing long-term management strategies. Resource managers can use these tools and the information they provide to develop the best strategy to obtain desired management outcomes and to help maintain the environmental and socio-economic benefits of forests in the face of climate change.

Tradeoff analysis and decision making

When management decisions are made with the goal of improving the flow of economic benefits, they can 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 on forest health, growth, and development. Managers and decision makers need straightforward methods to quantify the individual or combined benefits and tradeoffs of multiple, potentially conflicting, objectives. Different process-based ecological models were integrated for use at each pilot site (described above) to examine the tradeoffs associated with different forest management strategies in the context of a changing climate.

Multi-value tradeoff analysis framework

Development

A tradeoff analysis was also developed and applied to the MKRF site in British Columbia, Canada. The objective was to develop a conceptual framework for strategic planning using a meta-heuristic method to explore and understand tradeoffs among multiple indicators, and to potentially apply this framework to other Asia-Pacific

economies. In particular, the framework is able to assess the impacts of different forest management regimes on ecosystem values, evaluate the influence of different management alternatives on these values and their trade-offs/synergies, and address some of the complexities associated with the effects of climate change on ecosystems and the decision making process.

This framework involves the following steps: (1) evaluate existing information, such as the available forest inventory data and growth and yield information, and determine if there are any legal requirements within the forest (fish and wildlife habitats, endangered species habitats, visual quality requirement for tourism, etc.); (2) determine values or groups of values being considered in the analysis, such as timber volume, 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 and economic values. 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 management goals; (5) communicate the results.

The inventory-based forest ecosystem carbon budget model (CBM-CFS3) was employed to evaluate ecosystem carbon storage at MKRF for the current climate scenario. Ecosystem carbon budgets (i.e. total ecosystem carbon storage and net ecosystem carbon balance) are key indicators for SFM. Projections of carbon density for different time periods under the reference climate were calculated for the study area. Three alternative management scenarios were used: (1) current conditions, (2) mid-level emissions scenario RCP4.5 (Taylor et al. 2012), and (3) a scenario developed based on the notion that climate change may cause significant damage to BC's coastal infrastructure, including the reduction of pulp/timber mill availability. FORECAST Climate was used to simulate species and stand age responses to climate change.

Outcomes

A risk analysis was used to quantify the negative consequences associated with different scenarios. Regarding timber harvest volume, the temperature increase associated with RCP4.5 would accelerate timber supply but limited mill availability caused by climate change would significantly reduce production (Fig. 8a). However, net ecosystem productivity would not change significantly in any scenario because harvests always target older stands, which commonly have lower growth rates (Fig. 8b).

Risks associated with the trade-offs between the two comparative scenarios indicate that direct climatic forcing could cause an ecosystem response, but within the range of ecosystem recovery capability (or resilience) with almost no threats to society. However, indirect influences, such as reduced mill accessibility, could induce high-level threats to community livelihoods, while the net gain to ecosystems would not be significant. Furthermore, as harvest levels decrease, more forests grow older, making them more susceptible to natural disturbances (e.g., insects and diseases).

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. As such, a significant gain could be made by using this innovative framework as it can represent different management objectives through value system/indicator selections.

Model integration for decision making

Development

The aim of this research project was to assemble existing science, technology, and essential tools to help managers and decision makers make sound decisions for SFM under climate change. There are numerous tools/models used in SFM, strategic planning, and scenario testing to assist high-level decision-making. Our research explored the potential implications of these models in the AP with the expectation that some of these tools would be adopted by other regions to solve local management issues in a cost-effective manner.

Additionally, it developed a set of indicators for which SFM can be successfully evaluated under climate change. It selected 7 indicators for the study region as major indicators that may have a large response to climate change. Those indicators are: (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 developed from this research (e.g. FORECAST Climate, ClimateAP, niche-based models) to provide high-level SFM decisions (Fig. 9). There are three main components in this framework; the first component is the appropriate indicators and their models. Seven climate-related indicators were proposed and designed to be representative of key forest management objectives. The second component is the multiple values trade-off analysis framework for strategic

Fig. 8 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/year); **b** net ecosystem productivity (tC/year)
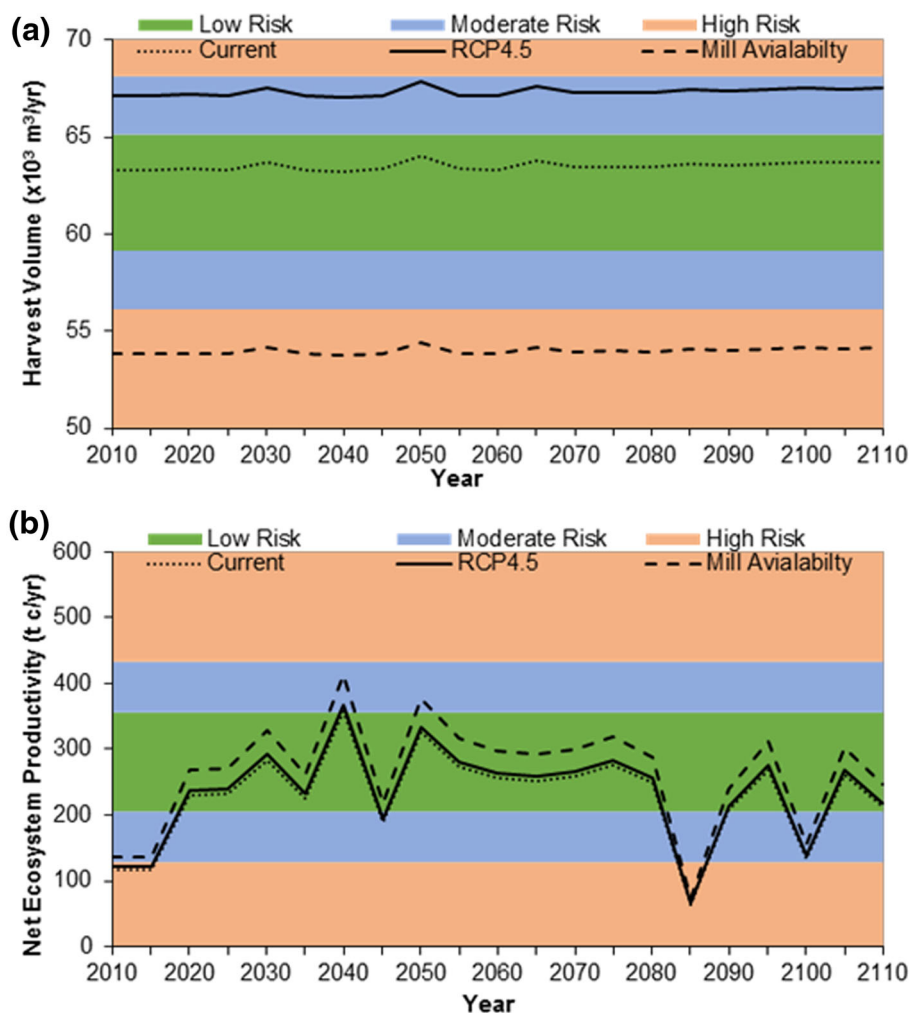
decision-making and planning. All the selected values/indicators and management objectives were formulated in a way that (sub)optimal solutions could be achieved through balancing or trading off one value for another/others. The last component is intuitive decision support and refers to information presentation. Results are presented using simple and intuitive risk classes to assist managers, practitioners and even general stakeholders in understanding complex forest management issues. This type of analysis is critically important, as it provides managers and planners with straightforward methods to quantify and assess the individual or combined benefits and tradeoffs of multiple, potentially conflicting, objectives of forest management.

## Fire management under a changing climate

Development

Forest fire is a crucial disturbance factor for forest ecosystems that can lead to large releases of carbon into the

atmosphere and decrease the carbon storage capacity of a forest. Climate change has already altered fire regimes and frequencies in some forest ecosystems (Flannigan et al. 2008) and future mitigation will require reducing the severity and frequency of fires. This research aimed to increase the understanding of the current and future relationship between forest fire and climate change, and to identify models best able to analyze the relationship between climate factors and forest fire properties in order to improve fire management and prevention. This was done through several research initiatives focused on Chinese boreal forests (Guo et al. 2014, 2015, 2016).

Outcomes

Researchers and resource managers need suitable models that can reflect the relationship between forest fire occurrence and climate factors in order to more accurately predict fires and develop realistic fire prevention and land management strategies. This project compared six generalized linear models to determine which was best suited to
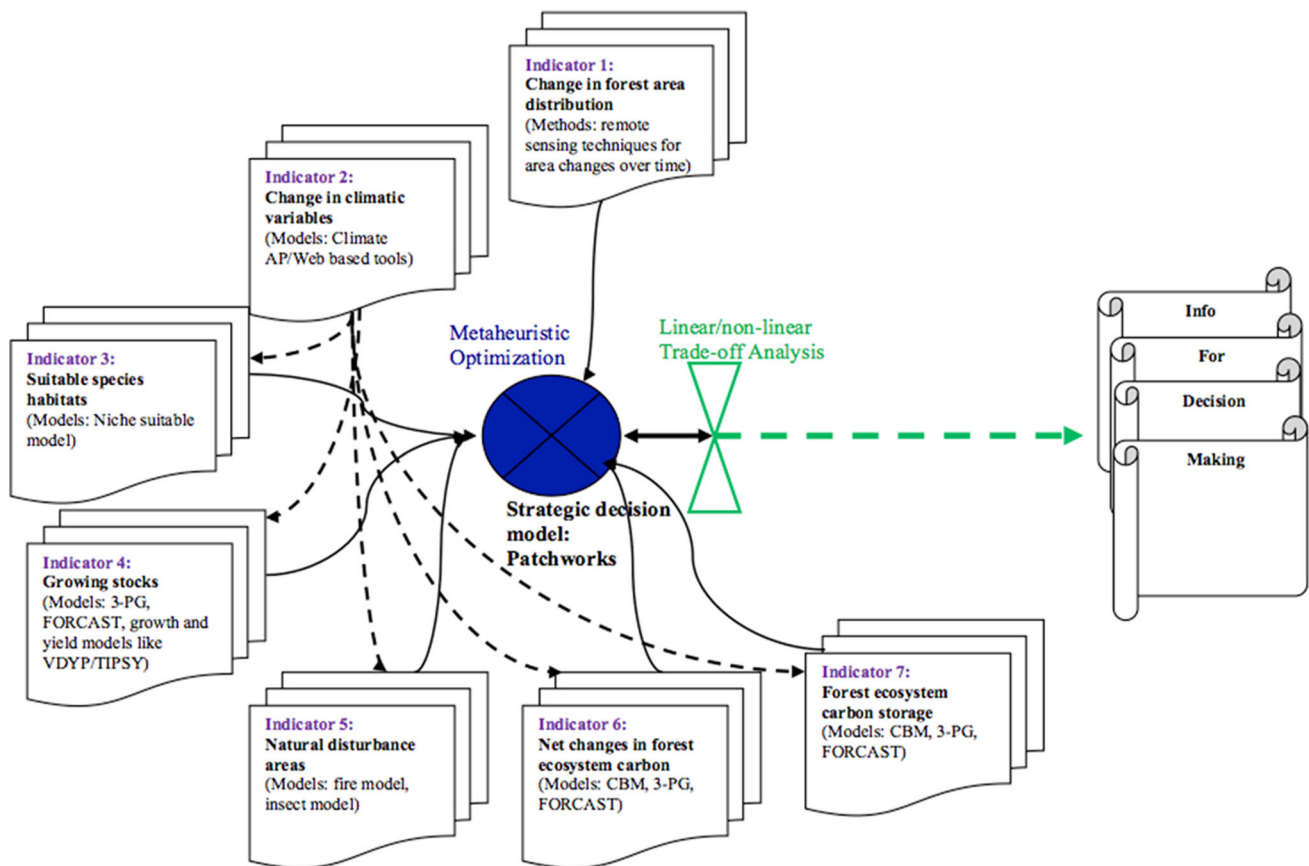
Fig. 9 A conceptual flow diagram of the indicator-based decision-support framework (Figure adapted from project website: http://asiapacific.forestry.ubc.ca/research-approaches/pilot-site-experiments/)

examine the relationship between the occurrence of lightning-induced forest fires and meteorological factors (Guo et al. 2016). It focused on the boreal forests of the Daxing'an Mountains in northeast China, which have the highest annual area burned in China. It used fire occurrence data from 1980 to 2005, focusing on lightning-induced fires. The selected meteorological variables where those previously determined to significantly impact fire occurrence in the region (Yu et al. 2007; Guo et al. 2010; Chang et al. 2013). To evaluate model appropriateness, it compared goodness-of-fit and tested the six models using the 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. Details of the models used, analysis methods and ranking of model suitability can be found in Guo et al. (2016).

In addition to fire occurrence frequency, burnt area is also an important concern for forest management agencies. This study aimed to identify a suitable model to reflect the relationship between area burned by forest fire and climate factors in the Chinese boreal forest (Guo et al. 2015). It used three regression models for the comparison. Response variables included burned area by lightning-caused fire, human-caused fire, and total burned area. Predictor variables were nine climate variables collected from a local weather station. It compared the goodness-of-fit of the models based on model fitting statistics such as R^2 (Rawlings et al. 1998; Hanna 2002), AIC, and root-mean-square-deviation (RMSE), and determined the most appropriate model for fitting fire data, as well as the main drivers of lightning- and human-induced fires. Details of the models used, analysis methods and results can be found in Guo et al. (2015).

Another component of this research was to determine the spatial and temporal patterns of historic human-caused forest fires and analyze the causes of the patterns, again in Chinese boreal forests (Guo et al. 2014). K-function and Kernel density estimation were used to analyze the spatial pattern of human-caused fires using S-plus and ArcGIS, respectively. 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. Significant spatial heterogeneity and seasonal variation were found in the distribution of human-caused fires in the Daxing'an Mountains. A logistic regression model was also developed to predict the likelihood of human-caused fires and identify the most influential variables in explaining the spatial pattern of fire occurrence. For full details on the analysis, methods and results, see Guo et al. (2014).

LiDAR

Development

As a primary carbon reservoir, forests play an important role in the global carbon cycle and have an immense capacity to contribute to climate change mitigation (Pan et al. 2011). However, there is still substantial uncertainty regarding carbon stocks and fluxes in forest ecosystems. In order to quantify the contribution of forest-related activities to climate change and evaluate the carbon storage potential of forests, biomass needs to be accurately measured and mapped. LiDAR was used to obtain accurate above-ground forest biomass data (Cao et al. 2014a) as it provides detailed, spatially explicit, three-dimensional information on vegetation structure (Lefsky et al. 2002).

Research was conducted on subtropical forests in Jiangsu province, China to build models for above- and below-ground biomass components using LiDAR, and to assess how forest type impacts model accuracy. Above- and below-ground biomass forest components were also mapped using LiDAR (Cao et al. 2014b). Another component of this research involved using small-footprint discrete (DR) and full-waveform (FW) airborne LiDAR to estimate forest biomass in Jiangsu province, China. It examined the relationship between forest biomass (e.g. above-ground and total biomass) and its components (e.g. foliage, root biomass) using LiDAR for three subtropical forest types—coniferous, broadleaved and mixed forests. Additionally, it examined the ability of DR and FW metrics to estimate biomass and evaluated the accuracy of these relationships for each forest type (Cao et al. 2014a).

Outcomes

Overall, LiDAR was found to be efficient in estimating the amount of biomass in subtropical forests, with performance results varying between specific forest types (Cao et al. 2014b). Although DR and FW LiDAR extract different forest data, both are useful in estimating biomass components in subtropical forests, and coupling them for modeling leads to better results than running them separately (Cao et al. 2014a). As well, forest type-specific models were more accurate than general models (Cao et al. 2014a). Overall, this research presents ways to improve measurements of forest biomass and carbon storage, and these are essential for accurate reporting of carbon fluxes and storage in forest ecosystems, as well as useful for forest management decisions and planning. The use of LiDAR to assess subtropical forest carbon stock should improve the accuracy of carbon estimates, provide better understanding of how ecosystems function in this region, and yield better preparation for and knowledge of the potential changes that will result from climate change. Full details on the analysis and results of this research can be found in Cao et al. (2014a, b).

Remote sensing

Development

Changes in environmental conditions as a result of climate change are expected to alter the timing and length of growing seasons, as well as vegetation structure and productivity. These vegetation changes may then alter trophic interactions (Tape et al. 2010) and carbon, hydrological and nutrient cycles (Ciais et al. 2005; Schwalm et al. 2010; Sturm et al. 2001, 2005; Zhao and Running 2010), as well as further reduce climatic stability (Anderson et al. 2010; Jackson et al. 2008).

Normalized difference vegetation index (NDVI) datasets were used in conjunction with climate data to understand how vegetation dynamics (e.g. annual productivity, seasonality, and minimum amount of vegetative cover) respond to climate change. Studies were conducted for the AP as a whole (Chen et al. 2014a, b; Xu et al. 2014b), with several focusing on China (Che et al. 2014; Xu et al. 2014a; Yan et al. 2013). This research involved investigating spatiotemporal changes in trends of vegetation dynamic indicators and climatic variables, as well as their relationship with land cover.

Remote sensing data were used to examine several different ecological and climatic relationships. NDVI was used to examine spatiotemporal changes in vegetation dynamics and climatic variables over the entire AP region (Chen et al. 2014a, b) and over China (Xu et al. 2014a) from 1982 to 2011. For the same time period, spatial and temporal variations in the end date of the vegetation growing season (EGS) were quantified and its relationship with climate factors were evaluated for the Qinghai-Tibetan Plateau, China (Che et al. 2014). For this research, global inventory modeling and a mapping studies (GIMMS) third-generation NDVI dataset (NDVI3g) derived from advanced very high resolution radiometer (AVHRR) were used. Leaf area index (LAI) was extracted

from the NDVI dataset for the Che et al. (2014) study, as it effectively reflects seasonal variation in vegetation. The data used is the only continuous and up-to-date global NDVI dataset that is regularly evaluated and assessed, and data trends are in agreement with those derived from Landsat (Beck et al. 2011) and moderate resolution imaging spectrometer (MODIS) NDVI data (Zeng et al. 2013).

For the research focusing on changes in vegetation from 1982 to 2011, 2 least-square linear regression models were used to evaluate changes in NDVI over the 30 year period (Chen et al. 2014a, b; Xu et al. 2014b) and to detect breakpoints (BP) resulting in two independent segments in the time series caused by a significant change in slope (Chen et al. 2014b). Piecewise regression was used to detect the turning point (TP), which differs from the breakpoint (although the slope before and after the TP are significantly different, the trend lines are still connected, whereas the trend lines before and after the BP are disconnected) (Chen et al. 2014a, b; Xu et al. 2014b). To determine the correlations between NDVI time series data and climate factors (temperature and precipitation), Spearman partial correlation (Chen et al. 2014a) was applied and a least-square regression model was used to include land cover in the correlation analysis (Xu et al. 2014b). Maps were generated for all analyses to ease visualization and understanding of spatial–temporal changes.

Outcomes

The mechanisms behind the temporal and spatial dynamics of vegetation productivity in the context of accelerated global environmental change are not well understood. However, this research has increased the understanding of spatial–temporal changes in vegetation dynamics and the influence of climate on these variables. The results of this research indicate that vegetation productivity and seasonality, as well as the relationship between vegetation growth and climate variables, vary among different subregions and ecosystems in the AP (Chen et al. 2014b; Xu et al. 2014a). Understanding of the importance of El Nino/Southern Oscillation (ENSO) on AP vegetation growth has also been improved by this research, and has been found to vary in its importance across the region (Chen et al. 2014a). Additionally, the spatial patterns observed in this research indicate complexity in vegetation growth dynamics, as well as a nonlinear response of vegetation to global climatic changes and other drivers (Chen et al. 2014b). This has provided insight into poorly understood yet very important relationships, which can now be further explored by building upon the findings of this research project.

Conclusions

This paper reviews the research done in the project *Adaptation of Asia-Pacific Forests to Climate Change* in order to summarize project achievements, disseminate results, and review the applicability of its models and tools to the AP region. The research covered an array of topics including climate, ecological, and process-based modeling, tradeoff analyses to aid in decision making, assessment of fire management and risk, evaluation of carbon storage and forest biomass using LiDAR, and examination of spatial–temporal relationships between vegetation growth and climate using remote sensing technology.

The outcomes of this research project have filled some critical gaps in knowledge and identified tools that are necessary to improve understanding of the impacts of climate change on forest ecosystems and to increase the adaptive capacity of Asia-Pacific forest ecosystems. The availability of a regionally downscaled climate model through the development of ClimateAP can facilitate and promote climate change related research and applications in the AP. The ecological models presented here allow an analysis of how changes in climate will influence climatic conditions, productivity, vitality, and ecosystem function of forest ecosystems and species within the AP. The tradeoff analysis techniques presented to evaluate the appropriateness of different management strategies in achieving certain objectives under a changing climate provide a unique opportunity to tailor research to specific regions and scenarios, which should improve the success of SFM planning. This research has also contributed to increasing the knowledge base regarding the current status, trends, and methods of evaluation of carbon storage and vegetation dynamics in the AP, as well as understanding of the relationship between climate and vegetation growth dynamics.

Although climate change is very apparent in the AP at a regional scale, its impacts and effects are diverse when examined more locally throughout the region. Models (climate or ecological) need to be tailored to specific issues, relationships and species in the location of interest to ensure that they are accurate and useful. The use of pilot sites in this project highlighted these differences and the need for locally adapted management objectives and model application.

Use of the tools and models reviewed in this paper will benefit not only the scientific community, but also a wide range of stakeholders and decision-makers. This increased knowledge and availability of tools will facilitate research, knowledge sharing, and ultimately lead to improved decision-making and management. The tools presented here

should be scaled up, as the site-specific application range of this project's outputs is minor compared to the scale of the AP region. Currently, this limits the use of results by policy makers and forest managers throughout the entire region. Extensions of this research should be conducted for other locations and tree species in order to increase the amount and quality of knowledge available to decision makers, researchers, and forest managers, and to increase the adaptive capacity of forests to climate change throughout the AP region.

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