Chapter 3
Forest Carbon Sequestration in Mountainous Region in Japan Under Ongoing Climate Change: Implication for Future Research

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Abstract Carbon sequestration is one of the most important ecological functions and services provided by forests in any catchment area. In addition, recent international framework requires detailed and accurate estimation of forest carbon stock, actual and potential forest carbon sequestration at national, regional, and administrative district scales under ongoing climate change. We, therefore, present an example of estimated change in potential carbon sequestration in a mountainous region of Japan under ongoing climate change at a spatial resolution of 1 km. In addition to (1) illustrating the importance of monitoring carbon processes in the field for simulating carbon fluxes at the regional scale and (2) characterizing changes in carbon sequestration in response to climate change in mountainous regions with large environmental gradients, we discuss (3) future directions of research on regional-scale carbon flux simulations from three distinct vantage points: ecological,

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forestry, and climatological/meteorological. Consequently, overcoming the challenges for three distinct vantage points will require not only further advances in individual disciplines but, also, interdisciplinary research by members of the ecology-atmospheric science community as well as transdisciplinary research linking ecology, forestry, and sociology.

Keywords Carbon sequestration · Forest · Global warming · Model simulation · Mountainous region

3.1 Introduction

Forest carbon sequestration plays a critical role in the global carbon cycle and is one of the main factors controlling the Earth's climate through biosphere–atmosphere interactions (Heimann and Reichstein 2008; Hui et al. 2015; Pugh et al. 2019). Accordingly, carbon sequestration is one of the most important ecological functions and services provided by forests in any catchment area (Chisholm 2010; Di Sacco et al. 2021). The Paris Agreement adopted at the 21st Conference of the Parties to the United Nations Framework Convention on Climate Change (COP21) held in 2015 committed signatory countries "to limit the global average temperature rise to well below 2 °C above preindustrial levels and to pursue efforts to limit the temperature increase to 1.5 °C" (IPCC 2018). A two-pronged approach for mitigating future global warming has thus been emphasized that includes the reduction of carbon emissions generated by human activity and the promotion of carbon sequestration by forests and other carbon sinks (Fawzy et al. 2020). This international framework requires detailed and accurate estimation of forest carbon stock, actual and potential forest carbon sequestration at national, regional, and administrative district scales under ongoing climate change (Lamb et al. 2021).

One of the main approaches to evaluating and forecasting future forest carbon sequestration for a given area involves the use of terrestrial ecosystem models (Cao and Woodward 1998a, b). Terrestrial ecosystem models typically consist of a physical module (water, heat, radiation balance, etc.) and a physiological module (photosynthesis, respiration, leaf phenology, carbon allocation, etc.) and enable estimation of carbon fluxes and carbon sequestration in terrestrial ecosystems (Bonan 2008). In terrestrial ecosystem models, forest carbon fluxes are expressed in terms of carbon absorption from the atmosphere via photosynthesis and carbon emissions to the atmosphere via respiration from different plant parts (leaves, branches, stems, roots) and respiration associated with microbial decomposition (Fig. 3.1). Changes in intensity and performance of various processes associated with photosynthesis and respiration in response to global warming are reflected in the carbon sequestration by forest ecosystems (Song et al. 2019). As such, in situ monitoring of fundamental carbon fluxes provides important basic information needed for forecasting future forest carbon sequestration (Ito et al. 2015). For example, among diagnostic research on the current state of forest carbon sequestration in Japan, ecological models validated by field data have been used to estimate

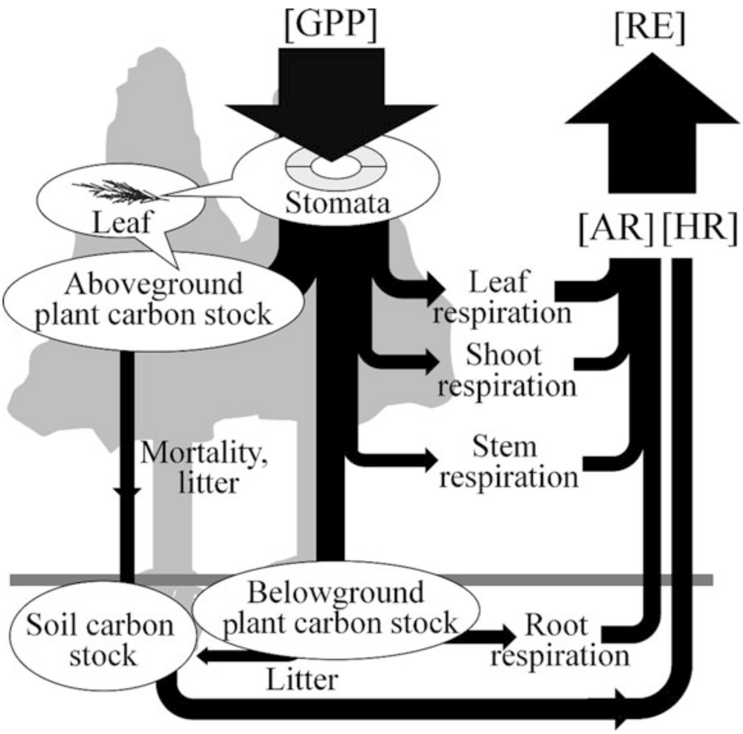

Fig. 3.1 Carbon allocation and partitioning in forest ecosystem. GPP is gross primary production, RE is ecosystem respiration, AR is autotrophic respiration, and HR is heterotrophic respiration

carbon sequestration at a spatial resolution of 1 km and to investigate environmental factors that govern this sequestration (Sasai et al. 2011; Setoyama and Sasai 2013). That said, although there are several studies that estimated future carbon sequestration in Japan at national and regional scales under ongoing climate change at a coarse spatial resolution (approx. over 10 km), much uncertainty remains (e.g., Sasai et al. 2016). One of the main reasons for this uncertainty has to do with the fact that 70% of Japan is mountainous, and there are vastly different climate zones ranging from 0 to 3000 m in elevation can be found within a horizontal distance of 100 km. The fact that forest mosaically cover 67% of the land area is likely another source of uncertainty. To be able to estimate future carbon sequestration in Japan at the administrative district (prefectural) scale, on the order of 10,000 km^2, it would be extremely useful to estimate carbon sequestration at a spatial resolution of 1 km or finer using ecological models that are validated and optimized using basic data obtained by monitoring forest carbon fluxes in the field.

In this chapter, we present an example of estimated change in potential carbon sequestration in a mountainous region of Japan under ongoing climate change at a spatial resolution of 1 km. In addition to (1) illustrating the importance of monitoring carbon processes in the field for simulating carbon fluxes at the regional scale and

(2) characterizing changes in carbon sequestration in response to climate change in mountainous regions with large environmental gradients, we discuss (3) future directions of research on regional-scale carbon flux simulations from three distinct vantage points: ecological, forestry, and climatological/meteorological.

3.2 Research Approach

3.2.1 Topography and Climate of the Target Site

We selected Gifu Prefecture, Japan, as the target site for simulations. Gifu Prefecture has a large elevation range (0 to greater than 3000 m above sea level) and experiences wide variability in annual mean temperatures and precipitation (approx. −3 to 16 °C; approx. 1800 to 3700 mm) (Fig. 3.2). Gifu Prefecture experiences distinct seasons: cold, dry winters; temperate springs and autumns; and humid and hot summers with a rainy season known as *tsuyu* in early summer under the East Asian monsoon zone. Higher elevation areas experience snow cover in winter.

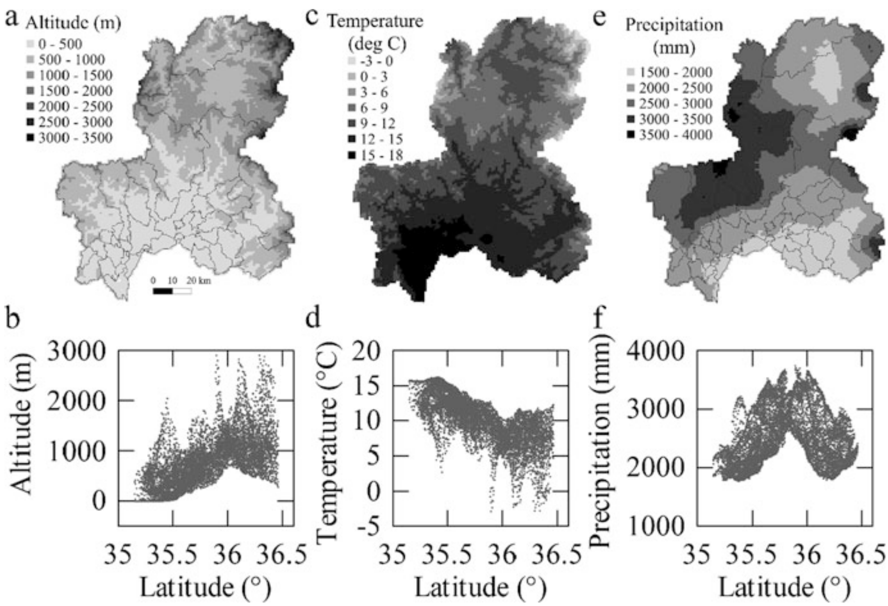

Fig. 3.2 Altitude, annual temperature, and annual precipitation under current climate condition

3.2.2 Model Validation Site

There are two flux tower sites in Gifu Prefecture: The Takayama evergreen coniferous forest site (TKC) (36°08′23′N, 137°22′15″E, 800 m a.s.l.) and the Takayama deciduous broad-leaf forest site (TKY) (36°08′46″N, 137°25′23″E, 1420 m a.s.l.). Descriptions of the vegetation and climate of both sites are provided in Table 3.1. The planted evergreen coniferous forest and natural or secondary broad-leaf forest are the two most common vegetation types in Gifu Prefecture and in Japan. In this study, we used forest carbon flux and stock data collected at these two sites to validate our ecological model.

3.2.3 Ecological Model

We used the Biome-BGC ecological model (version 4.2), which is capable of simulating carbon, water, and nitrogen fluxes in terrestrial ecosystems (Thornton 2010). The main components of ecosystem carbon flux in this model consist of a photosynthesis scheme, a carbon allocation scheme, an autotrophic respiration scheme, and a microbial decomposition scheme. Photosynthesis is primarily calculated using a photosynthesis model (Farquhar et al. 1980) and a stomatal

Table 3.1 Summary of vegetation and climate characteristics at Takayama evergreen coniferous forest (TKC) and Takayama deciduous broadleaf forest site (TKY)

	TKC	TKY
Vegetation type	Evergreen coniferous forest	Deciduous broadleaf forest
Dominant species	*Cryptomeria japonica* D. Don, *Chamaecyparis obtusa* Sieb. et Zucc.[a]	*Betula ermanii* Cham., *Quercus crispula* Blume[b]
Height of the tree canopy	20 to 25 m[c]	13–20 m[b]
Tree age	Approx. 40–50 years[a]	Approx. 60 years[b]
Understory vegetation	Sparse shrubs, herbs, and ferns[c]	Evergreen dwarf bamboo [(*Sasa senanensis* (Franch. Et Sav.) Rehder][b]
Annual mean air temperature	9.5 °C[d]	6.5 °C[e]
Annual mean rainfall	Approx. 1700 mm[d]	Approx.2100 mm[e]
Snow covered period	Late-December to late-March[f]	Early-December to mid-April[f]

[a] Saitoh et al. (2010)
[b] Ohtsuka et al. (2005)
[c] Lee et al. (2008)
[d] Average values from 2006 to 2010
[e] Saitoh et al. (2015)
[f] Visual inspection by using camera images (Nagai et al. 2018)

conductance model (Collatz et al. 1991). In the carbon allocation scheme, carbon fixed by photosynthesis is allocated to different plant parts (leaves, stems, coarse roots, fine roots, etc.) according to fixed ratios that are set in the plant physiology parameters. Autotrophic respiration is calculated as maintenance respiration expressed as a function based on temperature and plant nitrogen content plus growth respiration expressed as a proportion of productivity.

The ecological model is driven by daily maximum temperature, daily minimum temperature, daily average temperature, daily precipitation, daytime vapor pressure deficit, daytime solar radiation, and day length. In this study, we used the climate data set described in Sect. 3.2.4 as input data.

3.2.4 Climate Scenarios and Climatic Input Data

We used climate model output data (NAROv2.7r) obtained by statistical downscaling of five climate models (HadGEM2-ES, MRI-CGCM3, CSIRO-Mk3-6-0, MIROC5, and GFDL-CM3) (Nishimori et al. 2019). In this chapter, data from 1996 to 2000 were treated as current climate values and estimates from CMIP5 scenarios RCP2.6 and RCP8.5 as predicted future climate values for 2096 to 2100. For HadGEM2-ES, values for 2095 to 2099 were used as proxies for values for 2096 to 2100. We estimated daily average temperature, daytime vapor pressure deficit, daytime solar radiation, and day length using MT-CLIM module ver. 4.3 (Kimball et al. 1997; Thornton and Running 1999) based on output data from the five climate models (Toriyama et al. 2021). In this study, the atmospheric CO_2 concentration in 2000 is 369.4 ppm and it reaches 420.9 and 935.9 ppm in 2100 under RCP2.6 and RCP8.5 scenarios, respectively.

The climate models predicted that temperatures for Gifu Prefecture as a whole will increase compared to the current climate by 0.89 to 2.7 °C (mean = 1.9 °C) for scenario RCP2.6 and by 4.4 to 7.2 °C (mean = 5.3 °C) for scenario RCP8.5 (Fig. 3.3a). For both scenarios, most of the climate models predicted greater precipitation and lower solar radiation compared to current levels (Fig. 3.3b, c).

In this study, to reduce uncertainty in forest carbon sequestration estimates, we used mean values (e.g., daily maximum temperature, daily minimum temperature, precipitation, daytime solar radiation) obtained from the five climate models as input data for the ecological model. In Sect. 3.5.3, we report the results of using values from each of the five climate models separately as ecological model input values to illustrate the uncertainty of carbon sequestration estimates.

3.2.5 Model Simulations

First, to evaluate the accuracy of carbon flux simulations by the ecological model for evergreen coniferous forests and for deciduous broad-leaf forests, we ran model

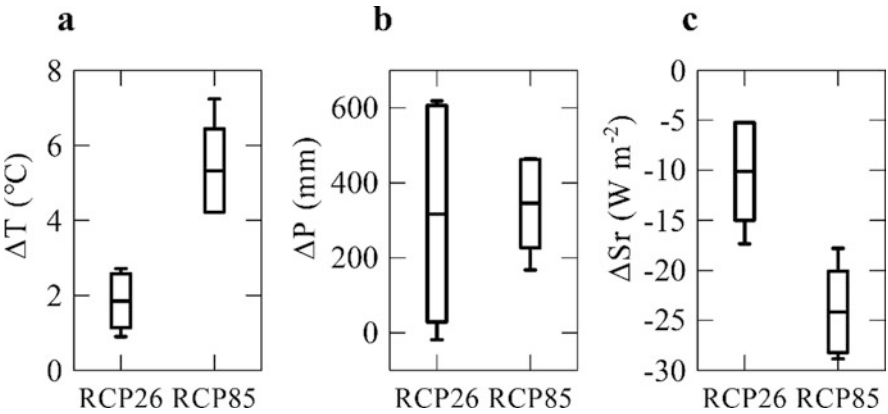

Fig. 3.3 The changes of annual temperature, annual precipitation, and annual solar radiation in the future projection relative to the current climate. Each box indicates average and standard deviation of five different climate model

simulations using meteorological data from the TKC and TKY sites (from 2006–2010 and 2002–2007, respectively) as input data. For the default simulation, we ran simulations using the default parameter settings for Biome-BGC v4.2. For modified simulations, we changed the parameters for evergreen coniferous forests and deciduous broad-leaf forests based on Toriyama et al. (2021) and Kondo et al. (2015), respectively, with some further modification and optimization.

For model simulations of Gifu Prefecture as a whole, we used the parameter sets from modified simulations. To eliminate the influence of stand age, in our analyses, we used five-year average carbon sequestration estimates for 46 to 50-year-old stands.

3.3 Importance of Field Research that Measures Actual Carbon Flux

The carbon flux of forests is expressed in terms of carbon absorption from the atmosphere through photosynthesis and carbon release to the atmosphere through respiration of various plant parts and microbial respiration associated with decomposition (Fig. 3.1). When major ecological disturbances such as fires, wind damage, snow damage, acid rain, or insect damage and non-CO_2 fluxes such as leaching, lateral transfers, harvesting, fire, herbivory, CH4, carbon monoxide, and emission of biogenic volatile organic compounds are not accounted for, net carbon sequestration can be expressed as net ecosystem production (NEP) using the following equation:

$$\text{NEP} = \text{GPP} - \text{RE} \tag{3.1}$$

where GPP is gross primary production (carbon fixed by photosynthesis), RE is respiration of the entire ecosystem consisting of plant respiration (AR = autotrophic respiration) plus respiration associated with microbial decomposition (HR = heterotrophic respiration) (Bonan 2008; Keenan and Williams 2018). NEP can also be expressed as follows:

$$\text{NEP} \cong \Delta\text{B} + \text{L} - \text{HR} = \text{NPP} - \text{HR} \tag{3.2}$$

where ΔB is the change in biomass, L is litter, NPP is net primary production, and HR is microbial respiration associated with decomposition. In addition, AR can be expressed as:

$$\text{AR} = \text{GPP} - \text{NPP} = \text{RE} - \text{HR} \tag{3.3}$$

Two methods can be used for monitoring each of these parameters: the eddy-covariance method and the biometric method (Chapin et al. 2006). The former method, calculate CO_2 exchange rate between ecosystem and atmosphere by measuring CO_2 concentration and 3-D wind speed at high frequencies (on the order of approximately 10 Hz) using observation towers, can be used to estimate all terms in Eq. (3.1) (Aubinet et al. 2012; Lee et al. 2004). The latter method estimates parameters via tree census or chamber method and can be used to estimate the terms in Eq. (3.2) (Ohtsuka et al. 2007). A certain level of uncertainty is associated with observations made using the eddy-covariance method and the biometric method. For example, measurements acquired at TKC and TKY using the two methods differ by approximately 40 g C m^{-2} $year^{-1}$ (Table 3.2). As such, whenever possible, it is best to use measurements obtained by both methods for model validation. Measurements for forest ecosystems in Global and East Asia obtained by both methods have been compiled and are available as Global dataset (Luyssaert et al. 2007) and, The Compilation Dataset of Ecosystem Functions in Asia (version 1.3) (Kondo et al. 2017; Chang et al. 2021), respectively.

Comparisons of default and modified simulation results (after parameter adjustment) and observed values from TKC and TKY sites are presented in Fig. 3.4 and Table 3.2. For both sites, modified simulations after parameter adjustment improved reproducibility of not only NEP but, also, other components of forest carbon flux and carbon stock (Fig. 3.4 and Table 3.2). As illustrated by this example, it is anticipated that the collection and publication of long-term continuous data using both methods over a wide range of ecosystems will facilitate improving the ability of ecosystem models to reproduce carbon fluxes.

Table 3.2 Performance of default and modified simulations of annual cumulative carbon fluxes and carbon stock in the evergreen coniferous forest at the TKC site and the deciduous broad-leaf forest at the TKY site

Site	Unit	Carbon flux and stocks	Default simulation	Modified simulation	Observation
TKC	g C m^{-2} $year^{-1}$	GPP	2330	2240	2220[a]
	g C m^{-2} $year^{-1}$	NPP	670	700	790[b]
	g C m^{-2} $year^{-1}$	NEP	90	390	390[a], 430[b]
	g C m^{-2} $year^{-1}$	RE	2240	1850	1830[a]
	g C m^{-2} $year^{-1}$	AR	1660	1540	1430[c], 1470[d]
	g C m^{-2} $year^{-1}$	HR	580	310	360[b]
	kg C m^{-2}	B	41.1	17.1	19.3[b]
TKY	g C m^{-2} $year^{-1}$	GPP	1260	1050	1000[e]
	g C m^{-2} $year^{-1}$	NPP	760	590	650[f]
	g C m^{-2} $year^{-1}$	NEP	30	170	250[e], 210[f]
	g C m^{-2} $year^{-1}$	RE	1200	880	750[e]
	g C m^{-2} $year^{-1}$	AR	500	470	350[c], 360[d]
	g C m^{-2} $year^{-1}$	HR	730	410	390[f]
	kg C m^{-2}	B	58.7	12.7	7.8[f]

GPP is gross primary production, NPP is net primary production, NEP is net ecosystem production, RE is ecosystem respiration, AR is autotrophic respiration, HR is heterotrophic respiration, and B is plant biomass

[a] Five years average (2006–2010) estimated using eddy-covariance method (Saitoh et al. 2010 and additional data)

[b] Four years average from May 2005 to March 2009 (Yashiro et al. 2010)

[c] The calculated value subtracted from GPP leaves NPP

[d] The calculated value subtracted from RE leaves HR

[e] Six years average (2002–2007) estimated using eddy-covariance method (Saigusa et al. 2005; AsiaFlux database)

[f] Five years average (1999–2003) estimated using biometric method (Ohtsuka et al. 2007)

3.4 Change in Carbon Sequestration Under Ongoing Climate Change

3.4.1 Elevation-Dependence of Cumulative Annual NEP Under the Current Climate and Contributing Factors

According to our simulations, under the current Gifu Prefecture climate with annual mean temperatures ranging from −2.9 to 16.3 °C, cumulative annual NEP was estimated to range from −32 to 515 g C m^{-2} $year^{-1}$ in evergreen coniferous forests and from −47 to 276 g C m^{-2} $year^{-1}$ in deciduous broad-leaf forests (Figs. 3.5 and 3.6). Furthermore, mean cumulative annual NEP for Gifu Prefecture (mean temperature for all grid squares: 10.5 °C) was estimated by simulations to be 436 g C m^{-2} $year^{-1}$ for evergreen coniferous forests and 229 g C m^{-2} $year^{-1}$ for deciduous broad-leaf forests. These simulated NEP values were similar to values

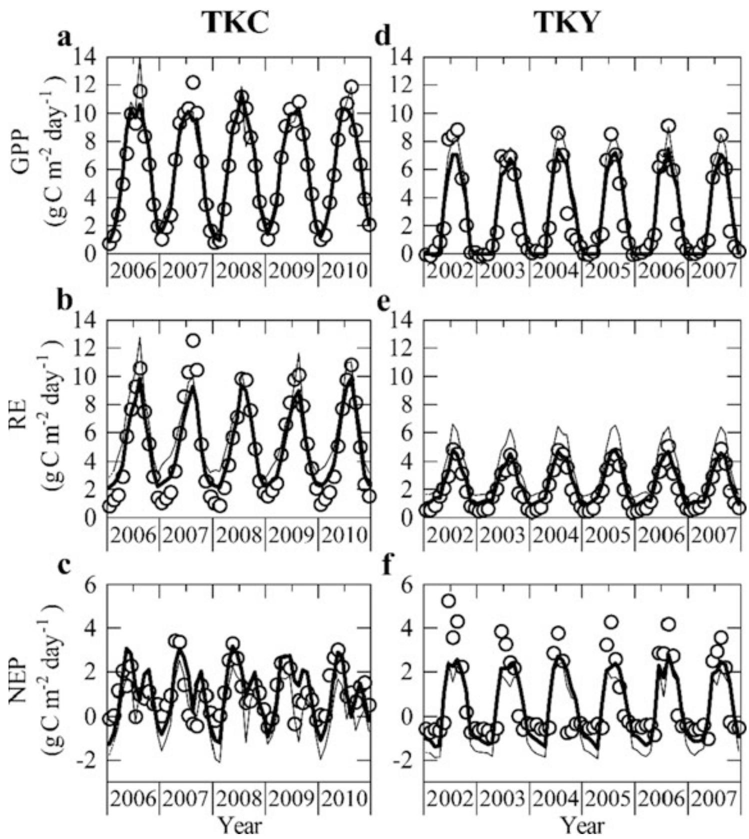

Fig. 3.4 Model performance of seasonal variation in gross primary production (GPP), ecosystem respiration (RE), and net ecosystem production (NEP) at Takayama evergreen coniferous forest (TKC) and Takayama deciduous broad-leaf forest (TKY) sites. Thin and solid lines indicate default and modified simulations, respectively. White circle indicates monthly values observed by eddy-covariance method at both forest sites

obtained previously in Japan using eddy-covariance and biometric methods: 290 to 479 g C m^{-2} $year^{-1}$ for evergreen coniferous forests (mean annual temperatures: 9.7 to 15.3 °C) and 258 to 357 g C m^{-2} $year^{-1}$ for deciduous broad-leaf forests (mean annual temperatures: 5.9 to 15.0 °C) (Table 3.3). Regarding the elevation-dependence of cumulative annual NEP, NEP tended to decrease with increasing elevation at elevations of 1000 m or higher in evergreen coniferous forests (typical mean annual temperatures of 10 °C or lower) and 500 m or higher in deciduous broad-leaf forests (typical mean annual temperatures of 13 °C or lower) but showed low sensitivity to elevation at lower elevations (Fig. 3.5c, f). These trends closely match the trends estimated for NPP with respect to elevation (Fig. 3.5b, f). In contrast, GPP tended to decrease with increasing elevation for all elevations (Fig. 3.5a, d). We attribute this result to the following three factors: (1) because

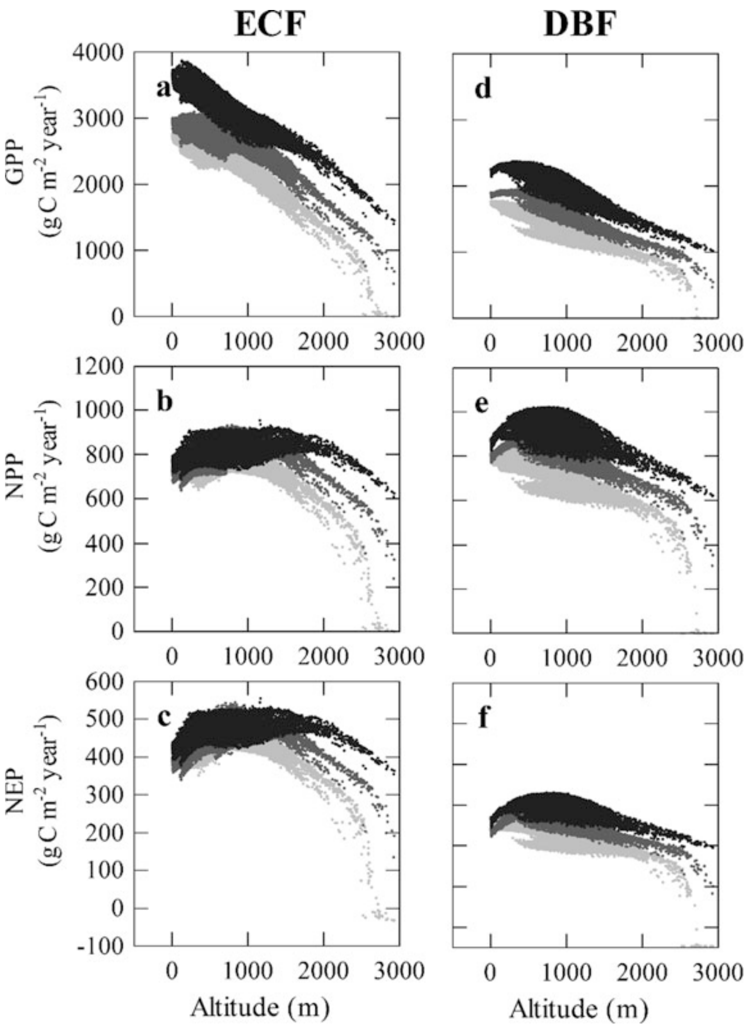

Fig. 3.5 Altitude dependency of (**a**, **d**) Annual GPP (g C m^{-2} year^{-1}), (**a**, **d**) Annual NPP (g C m^{-2} year^{-1}), and (**a**, **d**) Annual NEP (g C m^{-2} year^{-1}) under current (light grey), RCP26 future projection (dark grey) and RCP85 future projection (black) in evergreen coniferous forest (ECF) and deciduous broad-leaf forest (DBF)

mean annual temperature under the current climate is 20 °C or lower in this region, high temperature stress during summer is rare even in low-elevation areas and does not limit GPP; (2) because Gifu Prefecture is located in the East Asian monsoon zone, annual rainfall typically exceeds 1700 mm and summer rains known as *tsuyu* fall in June and July, summer drought stress has little impact on GPP; and (3) GPP and respiration exhibit different sensitivities to environmental factors.

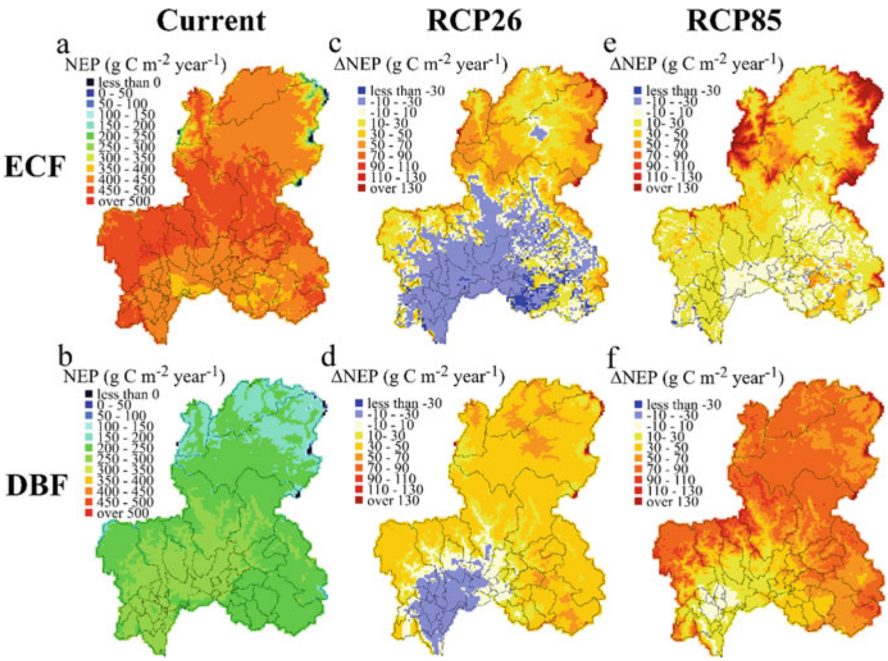

Fig. 3.6 (**a**, **b**) Annual NEP (g C m^{-2} $year^{-1}$) under current climate condition, (**c**, **d**, **e**, **f**) annual ΔNEP in the future projection relative to the current climate in evergreen coniferous forest (ECF) and deciduous broadleaf forest (DBF). Positive values in ΔNEP represent increased NEP in the future projection relative to the current climate

3.4.2 Spatial Distribution of Carbon Sequestration and its Control Factors

The spatial distributions of annual ΔNEP (predicted future NEP minus current NEP) are shown in Fig. 3.6. In both evergreen coniferous forest and deciduous broad-leaf forest simulations, whereas annual NEP in future climate projections tended to be higher than under the current climate in northern Gifu (i.e., low to moderate temperature zone), annual NEP tended to be slightly higher or lower in the south (i.e., high temperature zone) (Figs. 3.5 and 3.6). Meanwhile, annual ΔNEP showed low dependence on precipitation (Fig. 3.7). In the section below, we divide Gifu into high-, moderate-, and low-elevation zones and consider the factors contributing to ΔNEP in each of these zones.

In the high-elevation zone (generally with mean annual temperatures of 5 °C or lower), NEP was predicted to increase substantially under future climate in both evergreen coniferous forests and deciduous broad-leaf forests due to increases in summer productivity (Figs. 3.2 and 3.7). This effect was especially dramatic in the RCP8.5 scenario, which assumes the greatest temperature rise relative to present. Another contributing factor may be the lower magnitude of increase in respiration

Table 3.3 Annual cumulative net ecosystem production (NEP) in evergreen coniferous and deciduous broadleaf forests in Japan

Site Name	AsiaFlux site code	Forest type	Forest age (year)	Dominate species	Location	Annual temperature	Annual precipitation	NEP (g C m^{-2} $year^{-1}$)	References
Fujiyoshida	FJY	Temperate evergreen coniferous	90	*Pinus densiflora*	35° 27′ N, 138° 46′ E	9.7	2025	388[a], 290[b]	Mizoguchi et al. (2012), Ohtsuka et al. (2013)
Kiryu	KEW	Temperate evergreen coniferous	45	*Chamaecyparis obtuse*	34° 58′ N, 135° 59′ E	13.7–14.4	1179–1438	479[a]	Takanashi et al. (2005)
Kahoku	KHW	Temperate evergreen coniferous	32–55	*Cyptomeria japonica*, *Chamaecyparis obtuse*	33° 08′ N, 130° 42′ E	15.3	2130	427[a]	Ohtani et al. (2005)
Sapporo	SAP	Temperate deciduous broadleaf	90	*Betula platyphylla*, *Quercus crispula*, *Quercus mongolica*	42° 59′ N, 141° 23′ E	6.5	1100	261[a]	Nakai et al. (2003)
Tomakomai	TOE	Temperate deciduous broadleaf	45	*Quercus mongolica* var. *crispula*, *Acer mono*	42° 40′ N, 141° 36′ E	7.1	1200	258[a]	Shibata et al. (2005)
Appi	API	Temperate deciduous broadleaf	70	*Fagus crenata*	40° 00′ N, 140° 56′ E	5.9	2029	312[a]	Yasuda et al. (2012)

(continued)

Table 3.3 (continued)

Site Name	AsiaFlux site code	Forest type	Forest age (year)	Dominate species	Location	Annual temperature	Annual precipitation	NEP (g C m^{-2} $year^{-1}$)	References
Kawagoe	KWG	Temperate deciduous broadleaf	70	*Quercus serrata, Carpinus laxiflora, Purunus Jamasakura*	35° 52′ N, 139° 29′ E	15.0	1300	357[a]	Yasuda et al. (1998)

[a] Estimated value using eddy-covariance method
[b] Estimated value using biometric method

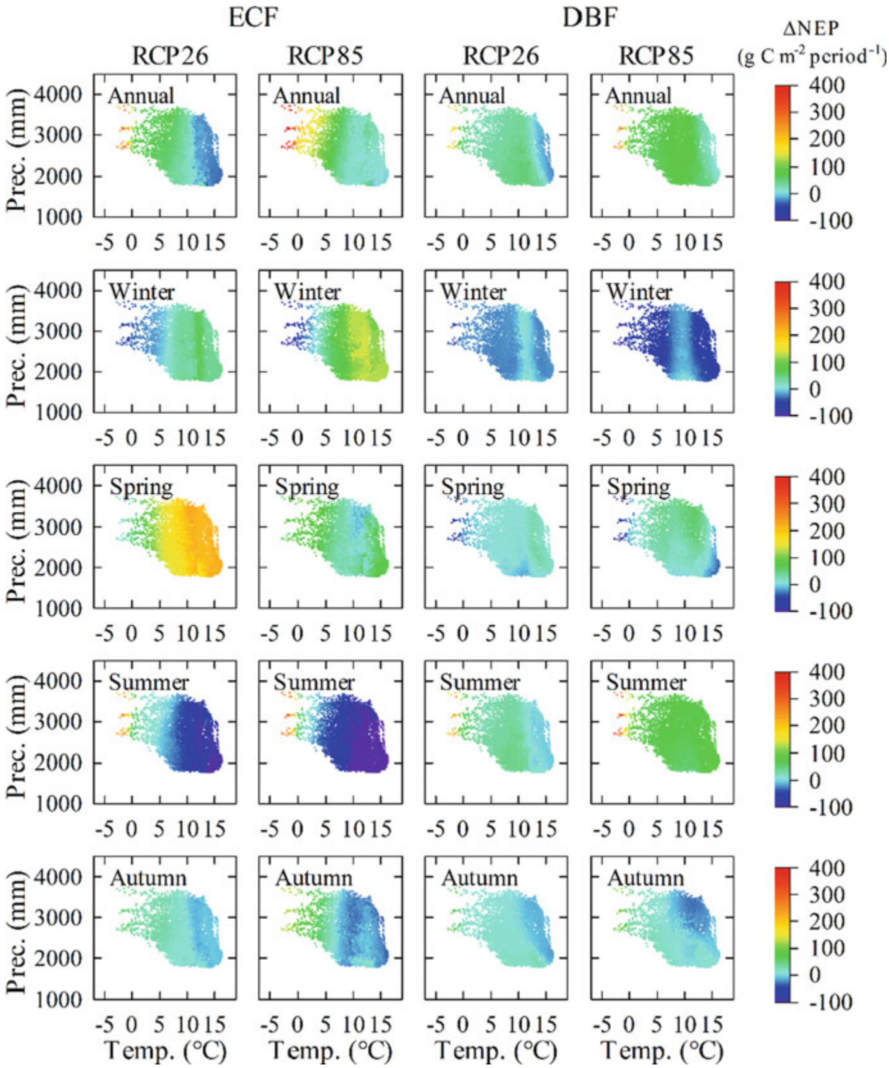

Fig. 3.7 Projected distribution of ΔNEP against annual temperature and precipitation under current climate in annual, winter (December–February), spring (March–May), summer (June–August), and autumn (September–November) periods in evergreen coniferous forest (ECF) and deciduous broadleaf forest (DBF). Positive values in ΔNEP represent increased NEP in the future projection relative to the current climate

due to soil organic matter decomposition compared to the moderate- and low-elevation zone. These trends are believed to reflect climate shift-driven conversion of high-elevation areas that are currently unsuitable for forest development into areas that are suitable for forest development.

In the moderate-elevation zone (typical mean annual temperatures between 5 and 10 °C), NEP was predicted to increase under future climate in both evergreen coniferous forests and deciduous broad-leaf forests. However, the mechanism is believed to differ between the two forest types. The increase in annual NEP of evergreen coniferous forests in future climate projections is thought to be the result of increased GPP due to warming-related improvement in photosynthetic function (Figs. 3.5 and 3.6). This effect appeared to be especially dramatic in winter and spring periods (Fig. 3.7). Investigations of cool-temperature evergreen coniferous forests in Japan based on camera monitoring and flux measurements suggest that, although the change in leaf area over an entire year is small (Nagai et al. 2012), high temperatures in early spring can increase photosynthetic potential and actual amount of photosynthesis by trees (Saitoh et al. 2010). In contrast, the increase in annual NEP of deciduous broad-leaf forests is thought to be due to an extension of the growth period due to warming. Regarding cool temperature deciduous broad-leaf forests in Japan, Saitoh et al. (2015) reported that acceleration of leafing in deciduous forests due to warming increases NEP, especially from spring to early summer. Meanwhile, NEP was found to increase only minimally or, in some scenarios, to decrease in the autumn—i.e., positive impacts of delayed leaffall were not observed. The main reason for this effect may be that cumulative light interception by the vegetation during the leaffall period, compared with leaf expansion period, was relatively low due to the different of solar elevation in both periods (Saitoh et al. 2015). Negative impacts of warming on NEP in the autumn have also been reported in North America and Europe (Piao et al. 2008). As can be seen from the above, although the mechanisms may differ between evergreen coniferous and deciduous broad-leaf forests, responses of leaf phenology to warming appears to be an important factor that should be accounted for when predicting NEP under warming conditions (Chung et al. 2013). Another possible contributing factor besides those discussed above is GPP increase due to CO_2 fertilization (e.g., Dusenge et al. 2019; Walker et al. 2021). The effect of CO_2 fertilization on GPP is current hot topics and future research is needed (e.g., Keenan et al. 2021; Wang et al. 2020).

In the low-elevation zone, whereas GPP was predicted to increase in both evergreen coniferous and deciduous broad-leaf forests (Fig. 3.5), increase in cumulative annual NEP due to warming tended to be inhibited, especially in evergreen coniferous forests. Like the moderate-elevation zone, the GPP increase in both forest types is thought to result from leaf phenology response to warming and CO_2 enrichment. The summer decrease in NEP in evergreen coniferous forests was especially dramatic compared to deciduous broad-leaf forests and kept cumulative annual NEP due to warming from increasing (Fig. 3.6). The substantial summer decrease in NEP in evergreen coniferous forests is believed to result from substantial warming-associated increase in plant respiration (particularly maintenance respiration), given that biomass in evergreen coniferous forests is higher than that in deciduous broad-leaf forests (Egusa et al. 2020).

The above results illustrate the possibility that, in mountainous regions with large environmental gradients, the impact of warming on forest sequestration differs substantially by climate zone and vegetation type even in an area as small as Gifu

Prefecture, which is on the order of 10,000 km^2. Furthermore, the results suggest that the changing carbon sequestration is determined by a variety of factors including the conversion of high-elevation areas unsuitable for forest development into areas that are suitable for forest development due to climate shift, leaf phenology response to warming, and warming-associated increase in respiration. In the next section, we will discuss the outlook for future research that emerges from the analysis above.

3.5 Outlook for Future Research

3.5.1 Ecological Perspective

3.5.1.1 Acclimation to Elevated Temperature and CO_2

Increases in temperature and atmospheric CO_2 concentration affect carbon sequestration through their influence on carbon metabolic pathways. One of the major challenges of ecosystem models is their treatment of changes in the temperature- and CO_2-sensitivities of carbon metabolic pathways (i.e., acclimation to elevated temperature and CO_2) (Dusenge et al. 2019). Previous simulated global warming experiments and free-air CO_2 enrichment (FACE) experiments have revealed that the acclimation of carbon metabolic processes to elevated temperature and CO_2 varies by tree and vegetation type (Ainsworth and Long 2005; Dusenge et al. 2020; Romero-Olivares et al. 2017). In response to this and other empirical evidence, many ecosystem models have been improved in recent years to account for acclimation to temperature and CO_2 (Smith and Dukes 2013). That said, regarding carbon estimation at the regional scale, the setting of parameter values related to temperature and CO_2 acclimation remains a challenge. For example, incorporating temperature and CO_2 acclimation into the model simulations discussed in this chapter would require the setting of parameter values that are appropriate for evergreen coniferous and deciduous broad-leaf forests in Gifu Prefecture. As a first step, this would require the compilation of data related to temperature and CO_2 acclimation for various vegetation types and tree species based on previously accumulated and new experimental results in a form that can be used to set parameter values in ecosystem models.

3.5.1.2 Change in Frequency of Extreme Weather Events and Forest Disturbances

It has recently been reported that climate change will very likely be accompanied by increased frequency of extreme weather events (IPCC 2018). Such extreme weather events are expected to impact terrestrial carbon sequestration through their disturbance of terrestrial ecosystems and mortality (Reichstein et al. 2013). For example, Allen et al. (2010) warn that climate change-related drought and heat stress will increase forest mortality across the globe, leading to a decline in carbon sequestration. Certain areas of Japan are predicted to experience increased frequency of heavy snows and higher-intensity typhoons (Nishijima et al. 2012; Sasai et al. 2019) that will result in higher frequency of large-scale disturbances and a decline in forest carbon sequestration. Meanwhile, the main causes of natural disturbances that impact ecological services such as forest carbon sequestration are known to vary by region (Thom and Seidl 2016). For example, the main causes of forest disturbances in the Gifu region discussed in this chapter include wind and snow damage in cool temperate mountainous areas (Nagai et al. 2018; Morimoto et al. 2021), as opposed to fire damage, which is frequently observed in the European Mediterranean region and North America (Seidl et al. 2014; Amiro et al. 2006). That said, as is the case with the simulation results presented in this chapter, previous studies estimating future changes in carbon sequestration at national and regional scales have not sufficiently factored in the increased frequency of region-specific extreme weather events that are expected to accompany climate change or the increased frequency of disturbances and mortality associated with such events.

Accordingly, the following items should be incorporated into future ecosystem model simulations of carbon sequestration at the regional scale: (1) extreme weather events particular to each region that have a high probability of impacting forest carbon sequestration; (2) spatial distribution of changes in frequency of extreme weather events due to climate shift and changes in magnitude of accompanying forest disturbances; and (3) impacts of forest disturbances on forest carbon sequestration.

3.5.2 Forestry Perspective

3.5.2.1 Land Use Change

Historical land use (change over time in land cover) impacts the current soil composition, soil organic matter content, soil nitrogen content, and other soil characteristics and, consequently, current and future forest carbon sequestration (e.g., Compton et al. 1998; Goodale and Aber 2001). In Japan, fallow fields and land are often afforested with Japanese cedar and Japanese cypress. As such, currently forested areas have not always been continuously used as forest land. Furthermore, because warming can cause climate shift in mountainous areas, in the future, forests may spread to elevations that are currently above the tree line. Thus, it is necessary to account for historical land use and future land-use change when estimating future forest carbon sequestration (e.g., Erb et al. 2013).

The first method of accounting for historical land use in model simulations involves the use of current soil environment data. For example, in their estimates of future NPP of Japanese cedar forests, Toriyama et al. (2021) accounted indirectly for historical land use by entering current soil environment data in their model.

The second method involves the use of remote sensing data. If the period in question is from 1970 onwards, satellite data (e.g., Landsat, EROS, etc.) can be used to reconstruct land use history and year-to-year land cover change. If the period in question is more recent than 1900, after the advent of airplane technology, aerial photographs taken by cameras installed on airplanes can be used. In Japan, for example, many aerial photographs taken by the US military after the end of the Second World War still exist. Although the information obtained is imprecise, it is also possible to estimate historical land use based on a survey of the literature. For example, in Japan, there are many works of literature from the Edo period from which the spatial distribution of historical land use from 1600 onward can be estimated. It is possible to reconstruct historical land use based on such data and to account for changes in soil composition, organic matter content, nitrogen content, and other soil parameters associated with land-use change by using this land-use history in the spin-up of model simulations.

Estimates of future land-use history will require construction of land-use scenarios that account for the impacts of human activity and climate shift.

3.5.2.2 Forest Management

Long-rotation forest management and the deployment/non-deployment and intensity of thinning are known to impact short- and long-term forest carbon sequestration (Canadell and Raupach 2008; Campbell et al. 2009; Aun et al. 2021). In Japan, the shortage of forest managers due to population ageing and decline is problematic and can potentially lead to abandonment of planted forests and increased area of un-thinned forests (Forestry Agency 2020). Problems specific to a given country or administrative district can be reflected in estimates of future forest carbon sequestration by incorporating specific data on the intensity of forest management into forest management scenarios that are then analyzed using ecosystem models (e.g., Wang et al. 2013). In fact, the updated version of the Biome-BGC model used in this chapter (Biome-BGCMuSo) includes an assignable thinning intensity parameter (Hidy et al. 2016). Estimates of future carbon sequestration that incorporate forest management information in this manner should prove useful in the formulation of forest management policy at the administrative district level.

3.5.3 Climatological and Meteorological Perspective

As shown by the simulations in this chapter, the impacts of warming on NEP vary substantially by elevation, vegetation type, and season. Accordingly, when estimating the effect of warming on future NEP even in a small area such as Gifu Prefecture, detailed climatological forecasting of the magnitude and spatial distribution of changes in environmental factors such as temperature, precipitation, solar radiation, and humidity for a given season is extremely important. These and other related challenges can broadly be classified into those having to do with the uncertainty of warming estimates from different models, the reproducibility of meteorological

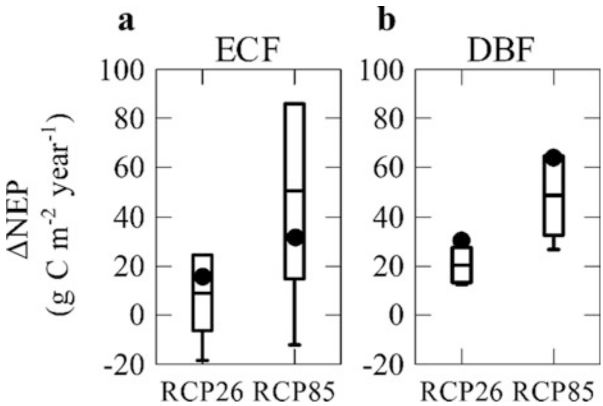

Fig. 3.8 The annual ΔNEP in the future projection relative to the current climate in Gifu prefecture, Japan. Each box and vertical bar indicate average and standard deviation, and maximum and minimum of ΔNEP simulated by each climate model (HadGEM2-ES, MRI-CGCM3, CSIRO-Mk3-6-0, MIROC5, and GFDL-CM3). Black circle indicates ΔNEP simulated by average meteorological values in five climate models

values in complex terrain, and warming-related changes in the frequency of extreme weather events.

First, there is substantial uncertainty regarding the magnitude of temperature rise, change in precipitation, and change in solar radiation associated with climate model warming estimates (IPCC 2013). In this chapter, to reduce uncertainty, we used average meteorological values (e.g., temperature, precipitation, solar radiation) from five climate models as input data for the ecosystem model (Fig. 3.3). Using meteorological values from each of the five climate models separately as ecosystem model inputs in scenarios RCP2.6 and RCP8.5 yields estimates of cumulative annual ΔNEP in Gifu Prefecture ranging from −18 to 19 g C m^{-2} $year^{-1}$ and −12 to 71 g C m^{-2} $year^{-1}$ for evergreen coniferous forests and from 12 to 28 g C m^{-2} $year^{-1}$ and 26 to 65 g C m^{-2} $year^{-1}$ for deciduous broad-leaf forests in scenarios RCP2.6 and RCP8.5, respectively (Fig. 3.8); the substantial breadth of estimates is especially evident for evergreen coniferous forest simulations. The above results highlight the importance of using output data from multiple climate models and discussing uncertainty when estimating future forest carbon sequestration.

Second, in the field of climatology, the reproducibility of meteorological values in complex landscapes including mountains is a challenge (Lundquist et al. 2019). The output values of the climate models used in this chapter are indirectly based on statistically downscaled 1-km climatic data and are able to reproduce elevation-dependent environmental changes with a certain degree of accuracy (Nishimori et al. 2019). That said, the models' ability to reproduce cloud- and water-related mechanical processes remains limited (Nishimori et al. 2019). Accordingly, reproduction of climatic values in regions with large environmental gradients such as mountainous areas requires the use of local climate models driven by the output of climate models around the target area as boundary conditions to recalculate the climate for the target area (i.e., nesting) (Gutowski et al. 2020).

The third class of challenges has to do with forecasting changes in the frequency of extreme weather events associated with warming. As extreme weather events do not necessarily occur every year, warming-related changes in frequency need to be expressed as probability density functions (Nosaka et al. 2020). This requires large-scale ensemble calculations with over 1000 runs. The Database for Policy Decision making for Future Climate Change (D4PDF) contains output from high-resolution 60- and 20-km-mesh climate simulations for the Earth and Japan (and surrounding areas). The data include 6000-years- ensembles (3000-years- ensembles for Japan and surrounding areas) of future climate simulation data based on present-day climate conditions as well as 5400-years- ensembles of future climate simulation data assuming a mean global temperature rise of 4 °C over pre-industrial levels, which is sufficient to enable changes in extreme weather event frequencies to be expressed as probability density functions (Mizuta et al. 2017). For example, Sasai et al. (2019) and Kawase et al. (2016) have used D4PDF to forecast increase in frequency of heavy snowfall events in certain areas of Japan. Such forecasts, as noted in Sect. 3.5.1.1, are useful for estimating changes in the frequency of extreme weather events and accompanying changes in the spatial distribution of forest disturbance intensity. Simulations based on temperature rise scenarios of 1.5 °C and 2.0 °C over pre-industrial levels have already been conducted (Nosaka et al. 2020); the results of these simulations should prove useful to future research aimed at estimating carbon sequestration in forest ecosystems.

3.6 Conclusions

In this chapter, we introduced our research involving the estimation of changes in carbon sequestration potential in mountainous regions of Japan under ongoing climate change at a spatial resolution of 1 km. In addition to demonstrating the importance of monitoring actual carbon fluxes in the field and characterizing the variability of carbon sequestration responses to climate change in mountainous regions with large environmental gradients, we discussed future directions for research involving regional-scale carbon flux simulations from three perspectives (ecological, forestry, and climatological/meteorological). Overcoming the challenges identified here will require not only further advances in individual disciplines but, also, interdisciplinary research by members of the ecology-atmospheric science community as well as transdisciplinary research linking ecology, forestry, and sociology.

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