Ecol Res (2015) 30: 201–210
DOI 10.1007/s11284-014-1205-7

SPECIAL FEATURE

Long-term and interdisciplinary research on forest ecosystem functions: Challenges at Takayama site since 1993

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Synergies between observational and modeling studies at the Takayama site: toward a better understanding of processes in terrestrial ecosystems

Received: 17 June 2014 / Accepted: 14 October 2014 / Published online: 18 November 2014

Abstract This paper reviews past and ongoing ecological studies at the Takayama forest site, one of Japan's long-term research sites with intensive studies; the emphasis here is on the synergies between observational and modeling studies. This synergism has been encouraged because global environmental change is a complicated and interdisciplinary issue that requires this type of collaboration. The increasing amount and quality of observational data available from this site helps researchers to better constrain their model simulations because substantial uncertainties remain in the behavior of models in their current form. In addition, modeling studies encourage observational research by integrating observational data within a comprehensive framework. They do this by demanding more long-term and high-quality data related to specific ecological processes, and by identifying high-priority processes and parameters that should be studied. We describe the types of modeling studies that have been conducted and how observational data from the Takayama site have improved the accuracy of these models. Many terrestrial ecosystem models have been applied to data from the site, both to validate the present forms of the models and to refine the structure and parameterization of the models. The development of new or improved terrestrial ecosystem models will be further facilitated by the requirements to simulate atmosphere–ecosystem exchanges and internal biogeochemical processes, as well as simulating their responses to a changing environment. We conclude by discussing the remaining research gaps and opportunities for deepening our understanding of terrestrial ecosystems through future collaborative studies.

Keywords Carbon cycle · Global change · Interdisciplinary research · Net ecosystem exchange · Temperate deciduous forest

Introduction

Terrestrial ecosystem models are widely used to simulate the general dynamics of ecosystems and to integrate a variety of observational data within a practical framework. The development of such models of the components of an ecosystem owes much to the concept of systems ecology that originated in the 1950s. Odum (1969) investigated ecosystem production and growth from a bioenergetics perspective and conceptualized energy and matter flows using compartmentalized models. The pioneering work of several Japanese researchers (e.g., Kira and Shidei 1967) also contributed greatly to the development of this field of research. In the early stages, mathematical models, especially those that provide an analytical solution, were preferred because they supported theoretical analyses and permitted long-term simulations at a lower computational cost (e.g., Olson 1963); the limited computational power available in the 1960s was an important consideration at the time. Furthermore, these models had difficulties in evaluating the effects of interacting environmental impacts on ecosystem dynamics.

Our increasing awareness of global environmental change has required ecosystem models to become more process-oriented, particularly from two perspectives. First, the models could not assume stable and unvarying environmental conditions because increasing levels of atmospheric carbon dioxide (CO_2) have been well doc-

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umented and because climatic change is ubiquitous on the earth. Therefore, terrestrial ecosystem models need to explicitly include the ability of the model to respond to changes in key environmental variables. Second, the models must be able to simulate non-steady states of an ecosystem, which result from environmental perturbations and anthropogenic disturbances. Importantly, models must simulate transient responses of the ecosystem to increasing atmospheric CO_2 and climatic change in the near future (e.g., during the 21st century).

Process-based models have been developed based on both ecological theory and empirical evidence derived from observational studies. In particular, well-organized datasets from a specific site have provided increasingly valuable insights (such as more than simply additive) that allow researchers to construct elaborate ecosystem models; these models provide deeper insights than models based on fragmented data from multiple sites. For example, the multi-decadal records from the Hubbard Brook Experimental Forest in New Hampshire, USA (Likens 2004) provides indispensable information on forest dynamics and biogeochemical cycles. Similarly, a biometric survey at the Pasoh Forest Reserve, in Malaysia, provides data from one of the few directly measured pristine tropical forests, leading to early development of a process-based carbon cycle model (Oikawa 1985). Through a series of refinements in the last few decades, mechanistic ecosystem models have been widely used in global change studies including climate projection by earth system models.

The present paper reviews the collaborations between observational and ecosystem modeling research that has been undertaken in the cool-temperate deciduous broad-leaved forest of Takayama, Japan; Takayama is one of the FLUXNET sites (Baldocchi et al. 2001) and is a long-term Japanese ecological monitoring station. We demonstrate how observational data from this site have been used to refine existing models or create new models, and, in turn, how modeling studies have provided insights into ways to interpret observational data. We conclude by discussing research gaps and opportunities for further synergistic research at Takayama, as well as discussing the implications for other sites and broader spatial scales.

Overview of collaborative studies

The Takayama experimental forest site (FLUXNET code, TKY) was established in 1993 on a mountain ridge in Gifu Prefecture in central Japan, which was covered by a typical secondary temperate deciduous forest of this region (Yamamoto and Koizumi 2005). The primary purpose of the site was to quantify atmosphere–ecosystem CO_2 exchanges and ecosystem carbon dynamics. Therefore, a flux measurement tower and permanent sample plot were installed at the site to allow assessment of the ecosystem-scale carbon budget through time using micrometeorological and biometric methods (e.g., Yamamoto et al. 1999; Ohtsuka et al. 2005). Advancing carbon cycle studies at the site required the documentation of specific ecophysiological and biogeochemical processes that would provide insights into the mechanisms underlying the observed rates and variability of carbon fixation. In particular, researchers with different methodological approaches needed to collaborate to allow the projection of future conditions and spatial extrapolations (such as, scaling up beyond point-scale measurements).

To accomplish this, several studies have been conducted using remote sensing and modeling approaches. In general, observational data related to the ecosystem carbon cycle have helped modeling researchers to calibrate their model parameters, such as carbon turnover rates, production capacity, and to validate the performance of their models. However, terrestrial ecosystem models are not always useful for observational researchers, who mainly work with field data and statistical analyses. In this regard, the Takayama research community was admirably organized to encourage collaboration among researchers from different scientific disciplines, such that many modeling researchers use data from the site and, in turn, contribute to deepening the understanding of ecosystem processes by observational researchers (Fig. 1). In particular, long-term and broad-scale simulations based on field observations show the spread of field data, while sensitivity analyses specify which parameters play important roles and where we have research gaps.

Simulations at the Takayama site

Because of the rich availability of long-term flux measurement and biometric survey data, several models have been applied to the Takayama site to validate model performance through a comparison with the observed values. Such comparisons reveal both the reliability of the modeling studies and difficulties that must be resolved through future research. Model confirmation is necessary because current ecosystem models are composed of many components and parameters (for example, they have a high number of degrees of freedom), which are only poorly constrained by theory and observational data. Figure 2 exemplifies the results of model intercomparison at the Takayama site, that is a part of the study at AsiaFlux sites by Ichii et al. (2013). It seems that terrestrial ecosystem models with different approaches and complexities captured the seasonal pattern of photosynthetic and respiratory CO_2 exchange, but that no model accurately simulated these fluxes. For example, most models failed to capture the beginning of net CO_2 uptake from the spring to the early summer and underestimated the strength of the mid-summer net CO_2 uptake (Fig. 2c). This suggests that the functions and parameters in the present models were not

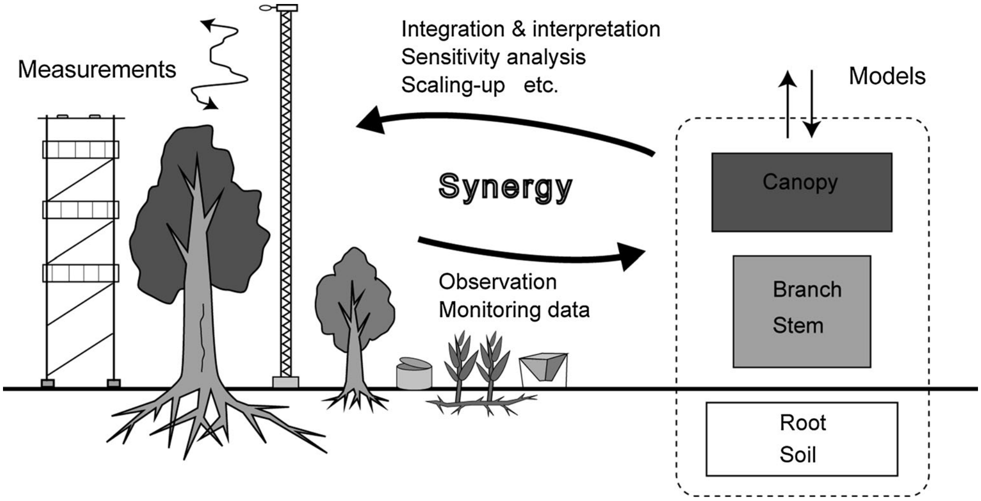

Fig. 1 Concept of the synergy between field observation and modeling to obtain better understanding of terrestrial ecosystem processes

determined with sufficient accuracy for this temperate deciduous forest.

In terms of the impacts of past disturbance, modeling studies have implications for interpreting the observed trends. The Takayama site was thought to have been logged during the 1950s and 1960s, but no records provided direct information about the times and intensities of the disturbance. Model-based sensitivity analysis provided an effective method to evaluate the impact of the disturbance. Ito et al. (2005) compared the simulation results between scenarios with and without logging impacts (represented by removal of 75 % of the biomass from the ecosystem) and found that the present carbon sequestration can mostly be attributed to ecosystem regrowth after a disturbance such as logging. Based on a simulation analysis using the Biome-BGC model, Kondo et al. (2013) suggested that including historical disturbance impacts improved the model's ability to simulate the present carbon fluxes.

Despite the number of modeling attempts, accurate simulation at the Takayama site remains challenging. The complex vegetation structure, which includes both deciduous canopy trees and a dense layer of dwarf evergreen bamboo grasses (*Sasa* spp.), makes it difficult to simulate energy absorption, and carbon gain and the interactions between the two vegetation layers. The region's monsoon climate results in strong seasonal variability in environmental conditions that is responsible for seasonal changes in the leaf traits of plants (Muraoka and Koizumi 2005). The volcanic soil (classified as an Andisol) at the Takayama site also has characteristic physical and chemical properties that differ from those of typical forest soils, making it difficult to apply the soil carbon schemes that have been developed for other sites. In terms of belowground processes, finding ways to include microbial activity and interactions with roots and soil organic matter is also an important challenge for carbon cycle models. These difficulties represent research opportunities; this will encourage modeling researchers to refine their models to better account for the site's vegetation dynamics and soil biogeochemistry.

Use of observational data by models

Observational data from the Takayama site enable model researchers to improve and examine their models. Table 1 summarizes the observational and modeling research activities that have been conducted at this site.

Eddy-covariance measurements show clear seasonal and interannual variability in the atmosphere–ecosystem exchanges of energy, water, and greenhouse gases such as CO_2. Even though these data have gaps and biases that result from the choice of methodology and the steep topography, they are sufficiently robust to allow comparisons of the timing of the seasonal pattern of CO_2 exchange and characteristic interannual variability. For example, Ito et al. (2005) used the flux measurement data of Saigusa et al. (2002) to examine the performance of a process-based model known as the Vegetation Integrative SImulator for Trace gases or VISIT model. The simple 'big-leaf' (for example, approximated by mono-layer) canopy scheme was able to simulate the clear seasonal pattern of CO_2 exchange [on a daily basis, the correlation between the model estimates and flux observations (R^2) was 0.57], although it has difficulty in capturing daily fluctuations. Sasai et al. (2007) applied the Biosphere model integrating Eco-physiological And Mechanistic approaches using Satellite data (BEAMS), a satellite-driven model, to data from the site. They found that the model successfully simulated the temporal change in gross primary production (GPP; on a monthly basis, $R^2 = 0.84$). Remarkably, field surveys conducted around the site have also allowed comparisons of partial CO_2 fluxes. For example, Lee et al. (2005) and Mo et al. (2005) conducted chamber measurements of soil respiration (the CO_2 efflux from the soil surface)

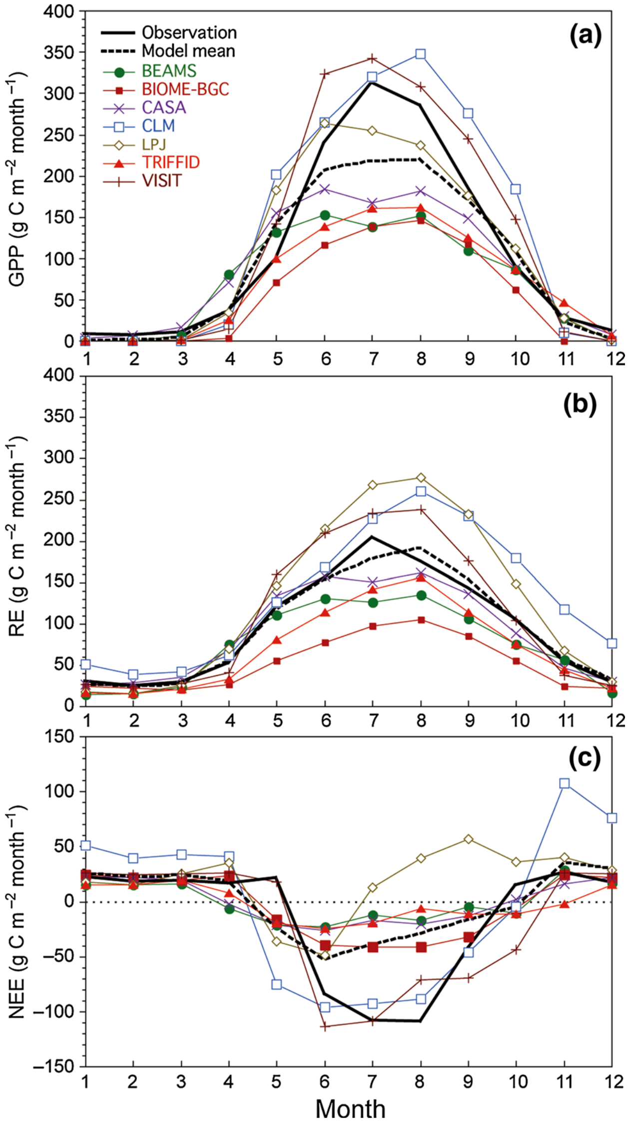

Fig. 2 The results of simulations by several terrestrial ecosystem models based on data from the Takayama site. Mean monthly **a** gross primary production (GPP), **b** ecosystem respiration (RE), and **c** net ecosystem exchange (NEE = RE–GPP) from 2000 to 2007. Data were obtained from Ichii et al. (2013); *BEAMS* Biosphere model integrating Eco-physiological And Mechanistic approaches using Satellite data by Sasai et al. (2007), *BIOME-BGC* Biome BioGeoChemical cycles by Thornton et al. (2002), *CASA* Carnegie-Ames-Stanford Approach by Potter et al. (1993), *CLM* Community Land Model by Oleson et al. (2008), *LPJ* Lund-Potsdam-Jena Model by Sitch et al. (2003), *TRIFFID* Top-down Representation of Interactive Foliage and Flora Including Dynamics by Cox (2001), and *VISIT* Vegetation Integrated SImulator for Trace gases by Ito (2010a)

at the Takayama site. Using their data, Ito et al. (2007) examined the accuracy of VISIT estimation for root and heterotrophic (microbial) respiration. However, they found vegetation dormancy and substrate depression, the non-linear temperature response around the freezing point, and low gas diffusivity caused by thick snow accumulation made it difficult to simulate winter soil respiration.

One remarkable advantage of the Takayama site is the co-existence of field surveys related to biomass and soil carbon storage and the associated ecophysiological properties. In fact, globally, few sites are represented by a set of biometric data, such as plant biomass, litterfall, soil carbon stock data, that correspond to flux measurements at a single location. Researchers have conducted elaborate long-term observations of vegetation and soil carbon dynamics at the Takayama site. Ohtsuka et al. (2005) measured net primary production at the site using a field survey of biomass growth and litter production. Ohtsuka et al. (2009) assessed net ecosystem production (NEP) from 1999 to 2006 and compared the results with flux measurements. They found that the site accumulated carbon at a rate of 1.4–2.96 Mg C ha^{-1} year^{-1}, which is approximately comparable with the flux measurement result of 2.59 Mg C ha^{-1} year^{-1}. This result also compares well with the value of 2.06 Mg C ha^{-1} year^{-1} obtained using the VISIT model (Ito et al. 2005). These types of analyses, based on different approaches, provide model researchers with more confidence in their simulation results and clarify research gaps in the present models. Ohtsuka et al. (2014) measured the amounts and analyzed the dynamics of coarse woody debris at the Takayama site. They found that dead biomass served as an important carbon stock that current terrestrial ecosystem models failed to adequately represent.

Many ecophysiological studies have also been conducted at the Takayama site, providing insight into the mechanisms underlying carbon-cycle processes. Muraoka and Koizumi (2005) measured seasonal variations in leaf properties (morphology and photosynthetic capacity) of the site's deciduous tree species. These data were used to parameterize leaf aging (Ito et al. 2006), leading to improved simulation of CO_2 exchanges. Sakai and Akiyama (2005) and Sakai et al. (2006) assessed the contribution of the understory composed mainly evergreen bamboo grasses to ecosystem carbon gain using field observations and model analysis. They found that the understory contributed about 25 % of total ecosystem GPP, strongly indicating the necessity to separate calculations of understory and canopy processes in ecosystem models.

The integration of field studies and satellite remote-sensing studies is an important characteristic of the Takayama site, and drives the satellite ecology (SATECO) initiative (Muraoka and Koizumi 2009). This observational linkage also benefits model researchers because it supplies canopy- to regional-scale data. For example, using the tracing radiation and architecture of canopies (TRAC) approach and litter-trap observation data, Nasahara et al. (2008) provide a credible estimate of the leaf area index (LAI) for each tree species, which is an important and representative parameter of ecosystem function and is observable from satellites. Muraoka et al. (2013) analyzed spectral vegetation indices for the canopy and related them to photosynthetic productivity. Their results have implications for terres-

Table 1 Observational and modeling studies previously conducted at the Takayama site at a range of spatial scales

Scales	Observations	Modeling	References
Organ (leaf etc.)	Leaf gas exchange Leaf morphology	Parameterization of leaf parameters	Ito et al. (2006) Kamakura et al. (2012) Noda et al. (2014)
Individual	Species, size Light absorption and production	3-D light transfer by the Y-plant model	Muraoka and Koizumi (2005)
Canopy	Fraction of absorbed PAR Leaf area index Phenology	Big-leaf, sun/shade leaf, and multi-layer schemes as a part in ecosystem models	Saitoh et al. (2012a, c) Sakai et al. (2006)
Ecosystem	Plant density Biomass and soil organic matter Net primary production Greenhouse gas concentration and exchange	Carbon dynamics by BEAMS, BEPS, VISIT, LSM, 3-PG, and TsuBiMo models Greenhouse gas modeling by the VISIT model	Alexandrov et al. (2005) Higuchi et al. (2005) Ito (2010a, b), Ito et al. (2007) Muraoka et al. (2010) Potithep and Yasuoka (2011) Inatomi et al. (2010)
Watershed and landscape	River runoff Satellite remote sensing	–	Muraoka and Koizumi (2009)
Region	Inventory Satellite remote sensing	East Asia carbon budget by the BEAMS and VISIT models Meso-scale meteorology by the LSM model Model intercomparison	Ichii et al. (2013) Ito (2008) Kuribayashi et al. (2013) Sasai et al. (2011) Yamaji et al. (2008)
Global	Atmospheric inversion Satellite remote sensing	Global carbon budget by the BEAMS	Sasai et al. (2007)

BEAMS Biosphere model integrating Eco-physiological And Mechanistic approaches using Satellite data, *BEPS* Boreal Ecosystem Productivity Simulator, *VISIT* Vegetation Integrated SImulator for Trace gases, and *LSM* Land Surface Model trial carbon cycle models, because knowing more about this relationship improved their ability to simulate seasonal and interannual changes in the CO_2 budget. Knowledge of seasonal variability of biological processes such as phenology is important for understanding the responsiveness of terrestrial ecosystems to environmental or climate change and is one of the priority research targets for remote-sensing researchers. At the Takayama site, leaf phenology has been thoroughly observed from spring bud flush to autumn leaf-fall (e.g., Saigusa et al. 2002; Nagai et al. 2013). Many ecosystem models contain a phenological scheme based on climatic data, in which leaf flush and fall dates are estimated based on climatic metrics such as the cumulative warmth above or below a certain critical temperature, respectively (Hadano et al. 2013). Determining the critical temperature and warmth is an important step for model simulations of seasonal deciduous ecosystems because temperature affects the period during which annual carbon gain occurs (Richardson et al. 2010). At the Takayama site, the continuous monitoring data have allowed model researchers to credibly determine the phenological parameters for the site. For example, Saitoh et al. (2012b) analyzed canopy phenology using on-site camera monitoring data and related the results to seasonal changes in GPP. These field-based collaborative studies also effectively linked ground observations to satellite remote-sensing data, with the goal of scaling up this approach to a regional scale. For example, Yamaji et al. (2008) estimated the NEP of temperate deciduous forests in Japan by scaling up flux data from the Takayama and the Hitsujigaoka sites, the latter on Hokkaido Island, in northern Japan, using the Moderate Resolution Imaging Spectrometer (MODIS) data. Also, Sasai et al. (2007) used the MODIS data and BEAMS satellite-oriented terrestrial ecosystem model to simulate atmosphere–ecosystem CO_2 exchanges at Takayama and extended this analysis to regional and global scales.

Long-term monitoring of data enables us to detect and analyze the impacts of extreme events such as disturbances and extreme weather conditions. Although the Takayama site has not experienced a severe heat wave or severe freezing since 1993, tropical cyclones disturbed this site and many other forests in Japan in 2004. The strong winds and heavy rains of tropical cyclones affect ecosystems by altering or severely modifying stand structure and exporting fallen materials into the river system. From June to October 2004, landfalls of ten tropical cyclones resulted in considerable defoliation at the Takayama site. Ito (2010b) analyzed the impacts of this wind-induced defoliation on the ecosystem carbon budget using a process-based model and a Monte Carlo approach. Using up-scaled flux data and meteorological data, Saigusa et al. (2010) analyzed the impact of the meteorological anomalies in 2003, a year with an unusually cool summer, on the carbon budget of East Asia. These analyses had valuable implications for interpreting observed temporal changes in a site's or region's carbon budget and in making future projections under the predicted changes now expected meteorological regimes.

An indirect but noteworthy pathway of collaboration between observation and modeling has been the combination of meta-analysis and site-data synthesis. For example, Baldocchi et al. (2005) investigated the seasonal onset of CO_2 uptake in temperate deciduous forest using flux data from 12 sites, including the Takayama site. They found evidence of a phenological rule that defines the relationship between temperature and the onset of ecosystem carbon uptake. Such findings from different sites should reveal details related to more general relationships that exist between environmental and biological factors; these findings are especially useful for improving ecosystem models. Moreover, inter-site analyses of flux measurement data have implications for regional-scale carbon budgets. For example, Kato and Tang (2008) analyzed the annual GPP, ecosystem respiration (RE), and NEP at 49 sites in Asia, including the Takayama site, and obtained several mean carbon uptake rates for representative biomes. Similarly, Hirata et al. (2008) analyzed the relationship between annual CO_2 fluxes and environmental conditions using observational data from 13 forest sites in East Asia, including the Takayama site. These studies, employing multi-site data syntheses, improve our understanding of regional-scale processes and our ability to describe these processes in simulations, such as Ito (2008) and Sasai et al. (2011). The Takayama site has played a leading role in these types of multi-site syntheses by providing well-managed data from a representative Asian temperate deciduous forest. Through these modeling and data syntheses studies, field observations at the Takayama site have made indispensable contributions to evaluations of Asian and global carbon budgets.

Future work at the Takayama site

Existing but unused data could be used in future work. Given the quantity and diversity of observations at the Takayama site, researchers have not yet used several components of the data in modeling studies. For example, high-precision measurements of the atmospheric composition and isotopic ratios (such as, $\delta^{13}C$ and $\delta^{18}O$ of ambient CO_2) have been obtained at the site (e.g., Murayama et al. 2005, 2010). Both above- and within-canopy air sampling has been conducted and these results could be used to describe local exchanges between the terrestrial ecosystem and the ambient air. Kondo et al. (2001) used the atmospheric CO_2 concentration data fro the Takayama site to examine the simulated daily variations using a simple parameterization of biological activity and regional-scale atmospheric transport. However, the data have not been fully used to examine and constrain terrestrial ecosystem models. Isotopic ratios provide additional information related to

CO_2 sources and sinks, as well as the exchanges between these pools that result from isotopic fractionation through assimilation and metabolic pathways. Kondo et al. (2005) also estimated the ratio of refixation of respired CO_2 within the canopy (up to 15 % in the summer) based on the carbon isotopic data collected at Takayama, thereby revealing the importance of canopy closure within the carbon cycle. These observational findings carry implications for improving terrestrial carbon cycle models. In addition, the isotope ratio data could be correlated with meteorological data at this site, such as stable carbon and oxygen isotope ratios in tree rings correlated with past climatic conditions (Kitagawa and Matsumoto 1995). This correlated data could be used to improve reconstructions of climate characteristics before the period when instrumental data is available, thereby providing additional proxies that can be used to assess climate change.

One of the distinctive observations conducted recently at the Takayama site involves in situ measurements of spectral reflectance of plant organs and of the entire forest canopy using spectroradiometers. Noda et al. (2014) provide a set of spectral reflectance data for representative tree species in Japan, including those from the Takayama site. Several recent studies have shown that these data can be used to estimate plant physiological traits such as the maximum carboxylation rate and the nitrogen content (e.g., Jin et al. 2012). The insights and knowledge derived from these elaborate measurements would also allow researchers to modify and improve terrestrial ecosystem models, especially those based on satellite data.

Since 2011, experimental warming facilities such as an open-top chamber warming system have been installed at the Takayama site. Although most of the observational data have not yet been published (as of June 2014), analysis of the data should clarify the responsiveness of leaf gas exchange, phenology, carbon allocation, and carbon budgets to changes in temperature under the current warming trends (Chung et al. 2013). In addition, a soil-warming system was installed at the site to allow researchers to examine the responsiveness of heterotrophic and soil respiration and of soil organic matter dynamics to increasing temperature (Noh et al. 2013). These data will be especially important for examining future model projections based on past observations such as those of Ito (2010a) and Hadano et al. (2013).

Requirements for additional data

Several sets of important data are not yet available from the Takayama site, and obtaining these data would lead to further expansion of the observational system. Additional observational data will enable us to validate models with higher confidence and encourage model development. By showing advanced simulation analyses, these models would be beneficial to observational researchers for exploring common research issues (such as, synergy with modeling; Fig. 1). For example, little data on nitrogen dynamics (such as Inatomi et al. (2010) for nitrous oxide flux) are available at the site, largely because of prioritization of studies related to the site's carbon-related properties. However, an increasing number of studies have suggested the importance of nitrogen as a limiting factor for photosynthesis and soil biogeochemistry at both local and global scales. To allow simulation of nitrogen dynamics by terrestrial ecosystem models, comprehensive data on nitrogen concentrations, flows, and regulating factors will be required; this data may be collected in conjunction with additional research studies on water and carbon dynamics. As Table 1 shows, landscape-scale models, such as Chen et al. 2004, have not been applied at the Takayama site, which suggests that there are important opportunities existing for studies of hydrology and of the nutrient budget of river catchments in and around the site.

Recent studies have shown that a large gap remains in our understanding of the belowground components of the ecosystem, such as root and soil carbon dynamics, and incorporation of this knowledge into terrestrial ecosystem models is lacking, such as can be seen in Ito et al. (2010) and Nishina et al. (2014). To reduce this uncertainty, further monitoring data on the dynamics of organic matter and on plant–microbe–soil interactions will be required. At the Takayama site, only some of these data have been obtained. For example, data have been obtained on the total carbon stock (Jia and Akiyama 2005), on fine-root biomass (Satomura et al. 2006), on the vertical distribution of the CO_2 concentration from soil to the air (Yonemura et al. 2013), and on coarse woody debris (Ohtsuka et al. 2014). However, we need additional data on soil chemistry, the composition and functioning of the soil microbial community, and on plant–soil interaction processes in the rhizosphere. Fortunately, monitoring data for soil respiration (e.g., Mo et al. 2005) can be used for ecosystem-scale validation of the carbon cycle models (e.g., Ito et al. 2007).

Advanced use of observational data

As we move into the era of "big-data", we are beginning to have access to masses of data that exceed our ability to handle and understand them. This statement seems to contradict the above-mentioned scarcity of data, but is nonetheless true for examples such as satellite remote-sensing data and long-term, high-resolution flux measurement data. We need advanced methodologies that will allow us to use very large amounts of observational data; in particular, this will allow us to deal with gaps and errors in the data. Recent developments related to data-oriented approaches have been driven by such requirements both in carbon cycle studies and in many other fields of research, such as meteorology and oceanography. Data-model fusion and data-assimilation techniques have been developed to include observational knowledge in numerical models (e.g., Luo et al. 2011). For example, Zobitz et al. (2014) used satellite-derived reflectance and CO_2 flux measurement data at a subalpine forest in the United States to optimize the parameters of a process-based model. This approach efficiently uses large amounts of data related to different ecosystem properties. At the Takayama site, few studies (e.g., Ito 2010b; Kondo et al. 2013) have attempted to constrain a terrestrial ecosystem model by using flux and biometric data. This means that we have many opportunities to make use of the Takayama data sets to derive ecological and biogeochemical insights, some of which have not been foreseen.

Acknowledgments A Grant-in-Aid from the Japan Society for the Promotion of Science (no. 26281014) supported this study. Dr. Kazuhito Ichii (Japan Agency for Marine-Earth Science and Technology) provided the model intercomparison results. The present authors thank all site founders, collaborators, and data managers working at the Takayama site.

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