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Key Points:

- The process-based ecosystem model shows better performance than empirical model in modeling monoterpene emission from a Japanese larch
- High emission of CO_2 in future will significantly influence the proportion between gross primary production and monoterpene emission

Supporting Information:

Supporting Information may be found in the online version of this article.

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Process-Based Modeling of Ecosystem-Level Monoterpene From a Japanese Larch (*Larix kaempferi*) Forest

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Abstract Globally, the emission of biogenic volatile organic compounds (BVOC) by plants represents the dominant source of volatile organic compounds emitted to the atmosphere. Monoterpenes, as the major BVOC group, can contribute to forming secondary organic aerosols and influence cloud properties. In this study, we developed a process-based monoterpene module in the Vegetation Integrative SImulator for Trace gases (VISIT) model by considering the production, storage, and emission of monoterpene as three main processes. We further evaluated the modeled monoterpene emissions against the ecosystem-level observation data at a half-hour scale at a Japanese larch (*Larix kaempferi*) forest site on Mt. Fuji, Japan. The VISIT model performed with relatively higher accuracy with a Willmott's index of agreement at 0.61, a mean bias error (MBE) at 0.29, and a root mean squared error (RMSE) at 0.43, comparable to that of Model of Emissions of Gases and Aerosols from Nature model with a Willmott's index of agreement at 0.63, a MBE at 0.40, and a RMSE at 0.54. In a long-term simulation under high CO_2 emission scenarios, the ratio between monoterpene emission and gross primary production exhibited a stronger correlation with CO_2 concentration than temperature. Our study provides a process-based modeling approach for more accurately simulating monoterpene emissions from Japanese larch.

Plain Language Summary This study focuses on constructing the process and improving the accuracy of simulating emissions of biogenic volatile organic compounds (BVOC), specifically monoterpenes, from a Japanese larch forest using the Vegetation Integrative SImulator for Trace gases model. By incorporating a process-based monoterpene module, the model demonstrated better performance compared to the widely-used Model of Emissions of Gases and Aerosols from Nature model. The simulated results showed temperature acting as the dominant factor in determining the proportion between gross primary production and monoterpene emission in the short term. In future projections, the analysis emphasized the significant role of long-term increases in CO_2 concentration in determining this proportion. This study provides a valuable tool for simulating site-based BVOC emissions, contributing to our understanding of the complex interactions between vegetation and the atmosphere.

1. Introduction

Plants emit large amounts of biogenic volatile organic compounds (BVOC) into the atmosphere (Peñuelas & Staudt, 2010). BVOC can be oxidized in the atmosphere to form secondary organic aerosols and lengthen methane lifetime, thereby affecting the global environment and climate change (Bai et al., 2017; Boy et al., 2022; Weber et al., 2022). Generally, Isoprene, monoterpene (MT), and sesquiterpenes are the dominant BVOC emitted by plants (Guenther et al., 1995, 2012).

Among the various types of BVOC, isoprene accounts for a major proportion (approximately 44%) of global BVOC emissions (Guenther et al., 1995, 2006). Consequently, isoprene has become the focus of research on the measurement and modeling of such emissions (Arneth et al., 2007; Potosnak, 2014; Young et al., 2009). Globally, the total amount of MT emission is less than that of isoprene (approximately 11%) (Arneth et al., 2008; Guenther et al., 1995). Nevertheless, the main MT-emitting plants such as coniferous forests cover expansive areas, especially the boreal areas of Siberia and the Arctic that are sensitive to climate change (Arneth et al., 2016; Tang et al., 2016; Zhang-Turpeinen et al., 2020). Changes in MT emissions from coniferous forests in these sensitive areas may have a significant impact on future climate changes (Bourtsoukidis et al., 2024). It is revealed that MT is widely involved in the ecosystem services provided by larch forests, including protecting trees from insect attack and impelling the occurrence of herbivorous predators (Arneth & Niinemets, 2010; Ghimire et al., 2022). Moreover, MT might play an important role in the decomposition process of forest soils by affecting crucial enzymes that control the material cycle (Adamczyk et al., 2015). Therefore, the determination of MT emission at the ecosystem level is important for an improved understanding of the impact of BVOC on ecological services.

MT is composed of two units of isoprene, and when released by a biogenic emitter, it mainly forms into α-pinene, β-pinene, or limonene, and the composition is highly dependent on the plant species (J. Chen & Griffin, 2005). The biological synthesis pathway of MT is analogous to that of isoprene: after isopentenyl pyrophosphate and dimethylallyl pyrophosphate are synthesized to intermediate products by mevalonate (MEV) and methylerythritol 4-phosphate (MEP) pathways, MT is produced under the intermediate products under the action of isoprenyl transferase and terpene synthase (Ameye et al., 2018; Potosnak et al., 2014; Q. Wang et al., 2019). The methylerythritol 4-phosphate pathway is connected to photosynthesis through one of the chief precursors, that is, glyceraldehyde-3-phosphate (G3P), which is produced by the Calvin cycle (Niinemets, Arneth, et al., 2010; Yang et al., 2021). Unlike isoprene, MT can be stored nonspecifically in plant leaves, lipid tracts, trichomes, and other storage organs, and the emission of MT from storage is more sensitive to temperature than to light (Niinemets & Reichstein, 2002). The emission rate of MT from a reservoir depends on residence time, that is, the duration of MT storage, which in turn relies on certain plant function types (PFTs) (Niinemets et al., 2002; Schurgers, Arneth, et al., 2009).

Environmental factors, including temperature, light, CO_2 concentration, weather history, soil water content, and nutrient condition will have influenced the biological production of terpenoid thus affecting the MT emission from the ecosystem (Arneth et al., 2016; Mochizuki et al., 2014; Niinemets, Monson, et al., 2010). Moreover, the emission dynamics of MT at the ecosystem scale are also influenced by other factors such as species composition and vegetation phenology (Arneth et al., 2008; Ghirardo et al., 2020; Hayward et al., 2001; Lun et al., 2020). Because MT is stored in some plants for a certain period and released thereafter, the emission scheme for modeling MT over the short term is deemed to differ from that over the long term (Arneth et al., 2007; Schurgers, Arneth, et al., 2009). Therefore, further elucidation of those emission mechanisms could help improve understanding of the long-term response of MT to future environmental changes.

Quantification of BVOC emissions on a regional or global scale primarily relies on modeling estimates (Arneth et al., 2007; Guenther et al., 2012). Currently, two mainstream modeling approaches are generally adopted. The first involves empirical data-driven models that are based on observed emission capacity and meteorological data, for example, Guenther's models such as G93, G95, G97, and the Model of Emissions of Gases and Aerosols from Nature (MEGAN) models (Guenther, 1997; Guenther et al., 1993, 1995, 2006, 2012). The second involves processed-based simulations to derive an explanation for how vegetation produces, stores, and emits BVOC, and to extrapolate that to the canopy and grid scales, for example, the Lund-Potsdam-Jena General Ecosystem Simulator (LPJ-GUESS) model (Arneth et al., 2007; Schurgers, Arneth, et al., 2009). Past studies indicated that results obtained from empirical simulations perform better in simulating observational data than those derived from process-based simulations (Bai & Duhl, 2021; Grote et al., 2010; Keenan et al., 2009). However, process-based models can explain the impact of plant photosynthesis on BVOC emissions, which has the advantages on connecting the climate change effects on photosynthesis and plant-originated BVOC emission (Arneth et al., 2007, 2008). Furthermore, Schurgers, Arneth, et al. (2009) proposed a MT emission algorithm with the production-storage-release process using the LPJ-GUESS model, with half the produced MT stored and the other half directly released, giving a basis of process-based simulation of MT emission. However, an isotope observation experiment (Ghirardo et al., 2020) found that the proportions of produced MT stored and released vary depending on plant type. Thus, there is still a need to further improve the representation of this MT emission process based on additional field observational data for different PFTs.

The main objectives of this work are to simulate MT emission and to explore the impacts of future climate change on MT emission processes at half-hourly scale from a Japanese larch forest ecosystem. We explicitly added the linkage between MT production and storage using a process-based dynamic ecosystem model, that is, the Vegetation Integrative SImulator for Trace gases (VISIT) model. This model integrates MT emissions with ecosystem gross primary productivity by investigating the influence of external conditions on ecosystem photosynthesis and determining the associated implications for MT emissions. The specific aims of this research were as follows: (a) to capture BVOC dynamics at half-hourly scale using the newly-developed VISIT model; (b) to quantify the sensitivity of modeled MT emissions to external environmental conditions, and (c) to explore the modeled MT emissions under various future climate scenarios.

2. Materials and Methods

2.1. Study Site and Data Set

The MT emission data measured by the relaxed eddy accumulation method at the Fuji Hokuroku (FHK) Flux Observation Site (35°26′N, 138°45′, located on Mt. Fuji in Yamanashi Prefecture, Japan), were acquired from AsiaFlux (https://www.asiaflux.net/). The FHK site is situated at an elevation of about 1,100 m with a slope ranging from 3° to 4°. The dominant plant species include *Larix kaempferi* (overstory) and ferns (understory), and the soil type is volcanic ash. Measurements of MT were performed at a height of 35 m above ground level using the relaxed eddy accumulation method and a gas chromatograph mass spectrometer (Mochizuki et al., 2014). Observations were conducted during the daytime from 1 May to 30 September 2011 (a total of 665 sets of measurements), and the measurement interval was 30 min.

We characterized both seasonal and diurnal changes in MT emission at the FHK site. For model current run (2006–2012), we utilized half-hourly meteorological data specific to the site. Additionally, the harmonized National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) hourly data (1979–2005) was utilized for model spin-up to fit to the FHK site. The spin-up lasts for 300 years and the data is randomly selected from input meteorological data. As the NCEP (CFSR) data is in 3-hourly, we used the sine squared function to fit the possible diurnal temperature and radiation change (half-hourly time step), evenly distributed precipitation over a day, and used daily-averaged relative humidity and surface wind speed at half-hourly time step.

2.2. VISIT Model

VISIT is a terrestrial process-based model that is based on the dry-matter production theory and simulates trace gas fluxes between the atmosphere and an ecosystem (Ito, 2019; Ito & Oikawa, 2002). The model is composed of carbon, nitrogen, and water cycling components, including their biogeochemical interactions (Ito & Inatomi, 2012). The carbon cycle component simulates photosynthetic CO_2 assimilation, allocation, autotrophic respiration, litterfall, and heterotrophic respiration, each of which is based on ecophysiological relationships and environmental responsiveness. Plant photosynthesis, called gross primary production (GPP) at the canopy scale, is simulated using a biochemical model coupled with a radiation transfer scheme (De Pury & Farquhar, 1997). By simulating forest structural development, the model allows us to estimate seasonal to decadal changes in leaf area index (LAI) and forest biomass. The model is driven by atmospheric composition (e.g., ambient CO_2 level) and meteorological variables (air temperature and pressure, surface precipitation, downward shortwave and longwave radiations, relative humidity, and surface wind speed). The model has been validated at a number of flux measurement sites (e.g., Ichii et al., 2013) and exhibited good capability to capture the observed CO_2 fluxes. Moreover, a model benchmarking study showed that the model can adequately capture the global-scale GPP across various biomes (Ito et al., 2017). The promising performance of the VISIT model in simulating vegetation dynamics and the carbon cycle indicates its potential to accurately capture the environmental responses of BVOC emissions from ecosystems.

2.3. Modeling Production-Storage-Release Process of MT

We enhanced the VISIT model by incorporating a MT emission module considering MT production and storage. The total MT emission rate is the sum of emissions from the storage pool and direct emissions from MT production (Schurgers, Arneth, et al., 2009). MT production is linked to photosynthetic electron transport and is influenced by temperature and atmospheric CO_2 concentration (Arneth et al., 2007; Guenther et al., 1993; Heald et al., 2009; Schurgers, Hickler, et al., 2009). The model also accounts for the storage of produced MT in a non-specific pool, using equations based on residence time and the fraction of MT transferred to the pool (Ghirardo et al., 2020; Niinemets & Reichstein, 2002; Schurgers, Arneth, et al., 2009). The measured emission of the Fuji study site is at the ecosystem level and the main source MT emitter is *Larix kaempferi* with its leaf-level emission capacity extrapolated at 2.97 μg gDW^{-1} hr^{-1} (Tani & Mochizuki, 2021). The equations and parameters used in this MT emission module are drawn from established literature and empirical observations (Text S1 in Supporting Information S1).

2.4. Model Calibration and Evaluation

The calibration process consisted of two parts. First, we adjusted the phenology-related parameters, specifically the critical growing degree days (GDD) thresholds for determining the plant growth periods, for correcting vegetation dynamics to fit with the observed seasonal ecosystem production and consumption indicators, that is, GPP, ecosystem respiration (ER), and net ecosystem production (NEE). Additionally, we also calibrated the monthly LAI values to ensure that they were within the observed range (extracted from the monthly Moderate Resolution Imaging Spectroradiometer (MODIS) LAI (MOD15A2) data set). Then, we calibrated the storage fraction and the residence time by comparing the root mean squared error (RMSE) between the model-predicted emissions and the observed emissions. The RMSE values are calculated when varying the storage fractions from 0.1 to 1.0 (interval: 0.1) and the residence time from 40 to 120 days (interval: 20 days). We used randomly-selected observed MT data (333 data points) for model calibration and the remaining observation data (332 data points) for model evaluation. Then, we used the index group (Willmott's index of agreement, mean bias error (MEB) and RMSE) to evaluate the performance of the model in simulating MT during the vegetation growing season (Tang et al., 2016; Willmott et al., 1985).

We further compared the results between the VISIT model and MEGAN model (Guenther et al., 2012). The MEGAN model stands as a commonly used data-driven tool for simulating monoterpene emission. Unlike the VISIT model, it introduces a fraction parameter to differentiate between light-independent and light-dependent emission sources (Table S1 in Supporting Information S1). Here we reset the light-dependent fraction (LDF) as the same value of the storage fraction (0.5) from the VISIT model. Furthermore, we compared the evaluation metrics (Willmott's index of agreement, MBE, and RMSE) between the process-based VISIT model and the empirical MEGAN model.

2.5. Future Projection

We obtained climate data from the sixth version of the Model for Interdisciplinary Research on Climate data set (MIROC6) for the future projections in this study (Tatebe et al., 2019). This data set encompasses surface temperature, precipitation, relative humidity, shortwave and longwave radiations, and surface wind speed. The model spans two distinct periods: 1900–2014 for historical run and 2015–2100 for future projections. Similar as processing NCEP (CFSR) data in Section 2.1, we used the same sine squared function to transfer the daily data to the possible diurnal change (half-hourly time step) for temperature and radiation, and the precipitation was evenly distributed throughout the day, while daily relative humidity and surface wind speed are equal the half-hourly.

3. Results

The results showed the model performance in simulating ecosystem carbon exchange and MT emissions. We compared the daily and seasonal MT changes derived from the VISIT and MEGAN models for May–October (plant growing period) 2011 to evaluate the model performance.

3.1. Model Calibration and Evaluation

As MT production is linked to carbon assimilation of the main plant species (*Larix kaempferi*) which contributing to most carbon production in this ecosystem, we first compared the average daily simulated GPP (RMSE = 1.77 gC m^{-2} d^{-1}, R^2 = 0.88), ER (RMSE = 1.74 gC m^{-2} d^{-1}, R^2 = 0.71), and NEE (RMSE = 1.87 gC m^{-2} d^{-1}, R^2 = 0.48) by the VISIT model with observed data from the FHK site in 2011 (Figure 1). The simulated daily GPP was generally close to the observation, whereas the daily ER was underestimated by approximately 15% compared with the observed values. The largest variation between the simulated and observed ER values might reflect insufficient consideration of the impact of soil nutrients on microorganism respiration activities (Takagi et al., 2015; Takahashi et al., 2015; Ueyama et al., 2013).

The simulated LAI of the overstory trees of the studied ecosystem in 2011, shown in Figure S1 in Supporting Information S1, well fits the range of MODIS LAI values at the FHK site during the growing period (May–October). Owing to differences in the spatial scale between the LAI data sources and the observable LAI from understory plants during tree leaf fall, there are certain discrepancies between the simulated LAI and the MODIS LAI, especially noticeable during the non-growing seasons when the MODIS LAI values are higher than the simulated LAI values. We found that under the optimal pool-based parameters, with storage fraction at 0.5 and

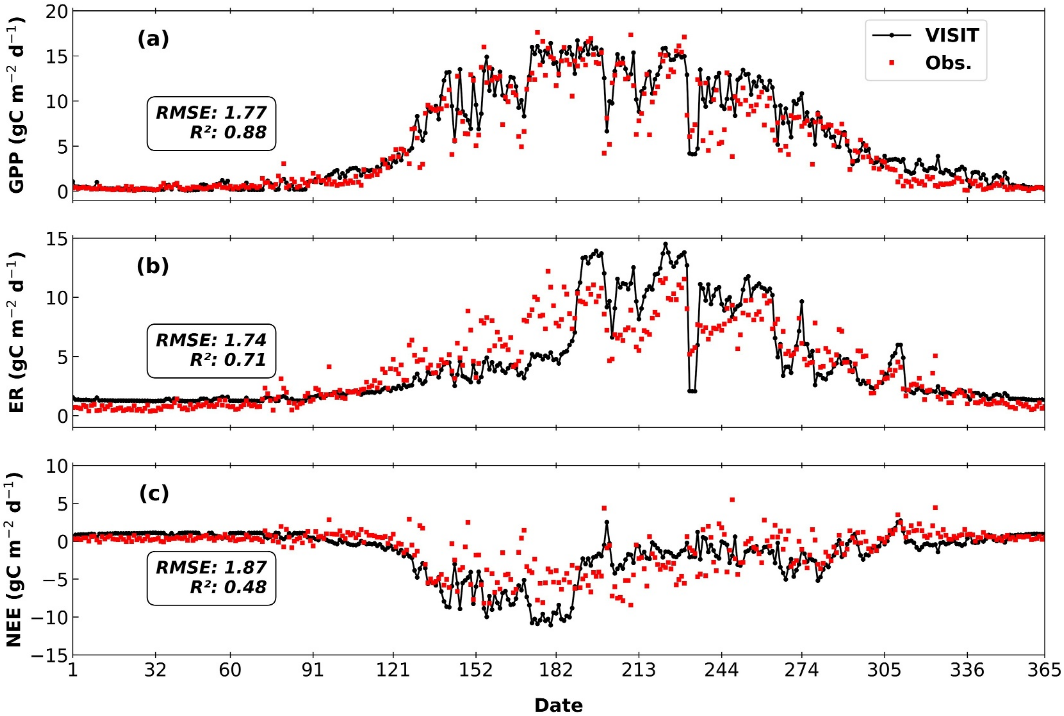

Figure 1. Simulated (black line) and observed (obs., red dots) daily fluxes of (a) gross primary production (GPP), (b) ecosystem respiration (ER), and (c) net ecosystem exchange (NEE) in 2011 (the evaluation values include the root mean squared error and coefficient of determination (R^2) between the modeled and the observed values).

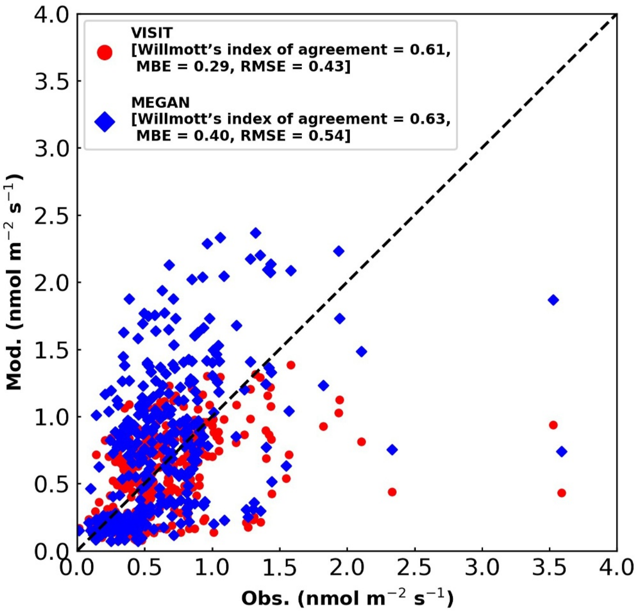

Figure 2. Willmott's index of agreement, mean bias error (MBE) and root mean squared error (RMSE) for the observed and modeled MT for both of the Vegetation Integrative SImulator for Trace gases (VISIT) and the Model of Emissions of Gases and Aerosols from Nature (MEGAN) models. The agreement between the modeled output and the observed values is more acceptable when the value of Willmott's index of agreement tends toward 1 and the values of MBE and RMSE tend toward 0.

residence time at 100 days, the modeled results from the VISIT model showed the lowest RMSE (0.45) with the observation (Figure S2 in Supporting Information S1); thus, we used this value in further validation and future projection processes.

The model evaluation indicators, that is, Willmott's index of agreement and MBE and RMSE, between the two emission schemes are shown in Figure 2. The Willmott's index of agreement for the VISIT model (0.61) is marginally lower than that of MEGAN (0.63), indicating that MEGAN performs a slightly better predictive variance and distribution than the VISIT. However, the VISIT model (MBE = 0.29, RMSE = 0.43) significantly surpasses the MEGAN model (MBE = 0.40, RMSE = 0.54) in terms of error comparison. This implies that VISIT still exhibits better performance, as indicated by the notable discrepancy in the MBE and RMSE values, while both Willmott's indices of agreement remain within an acceptable range.

We further explored the short-term responses of the VISIT and MEGAN models to environmental factors and plotted the response curves of these models to light and temperature (Figure S3 in Supporting Information S1). We find when temperature exceeds 25°C, the MEGAN model exhibits a stronger response to temperature compared to the VISIT model (Figure S3a in Supporting Information S1), and this difference is particularly pronounced after 30°C. Both VISIT and MEGAN models demonstrate similar responses curves to light, while VISIT performs more sensitive to low light conditions (Figure S3b in Supporting Information S1).

The comparisons between model simulations (both VISIT and MEGAN) and observation data during plant growing seasons are indicated on Figure 3a.

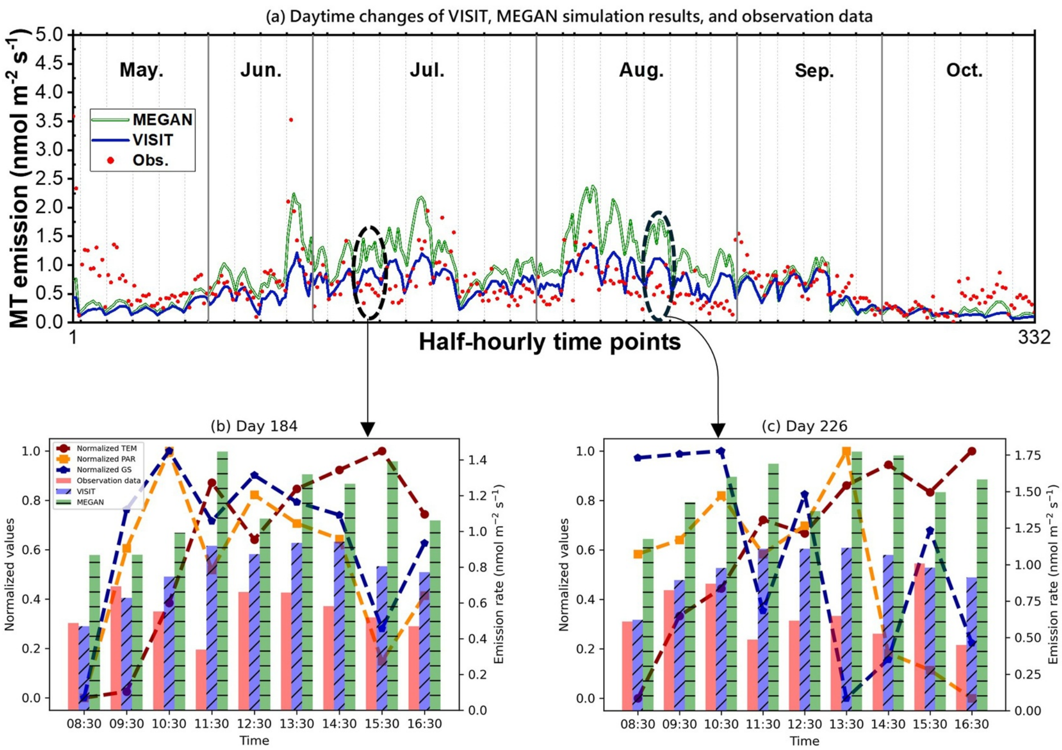

Figure 3. Daytime changes of simulated MT results (a) by Vegetation Integrative SImulator for Trace gases (VISIT) and Model of Emissions of Gases and Aerosols from Nature (MEGAN) models with two examples of relevant changes of environmental conditions on day 184 (b) and day 226 (c) (normalized conditions in one day: TEM: Temperature; PAR: modeled absorbed photosynthetically active radiation by VISIT; GS: modeled stomatal conductance by VISIT).

MEGAN model shows an obvious overestimation in modeling MT emission, especially between June to August. In addition, to understand the different responses to temperature, light (indicated by modeled PAR) and water (indicated by modeled GS) between VISIT and MEGAN model, we presented two 30-min daytime changes of MT emission with the changes of above indications as examples (Figures 3b and 3c). During the period from 14:30 to 15:30 on day 184 (Figure 3b), We found a decrease in MT emissions associated with reduced light and modeled GS (suggesting a lower photosynthesis rate). Notably, the VISIT model results follow this decline trend with observed MT emissions during this period, while the MEGAN model simulates higher emissions due to the elevated temperature during this period.

Moreover, during the period from 11:30 to 12:30 on day 226 (Figure 3c), where stomatal conductance and light increased while temperature decreased, MEGAN results exhibited a decline. In contrast, VISIT results remained relatively stable, closely resembling the trend of observation, which showed a slight upward tendency. This suggests that the reduced MT emission by lower temperature is offset by the increased MT production due to the increasing PAR. However, the notable decline in MEGAN results underscores the high sensitivity to temperature, potentially overshadowing the impact of other factors on its performance.

3.2. Scenario-Based Future MT Emissions

We present the site-based future MT emissions from the FHK forest ecosystem dominated by *Larix kaempferi* under four SSP scenarios (Figure 4) by using the VISIT model. All scenarios show an obvious increase in future MT emissions between 2020 and 2060. Particularly, after 2060, the model forecasts an upward trajectory in MT emissions under the high CO_2 scenario (SSP585), contrasting with a comparatively stable trend under the other scenarios, especially in SSP119 scenario.

The VISIT model predicts MT emission rates during 2015–2100 of 0.1–0.18 nmol m^{-2} s^{-1} (approx. equivalent to 0.38–0.68 gC m^{-2} $year^{-1}$) under the SSP585 scenario and of 0.1–0.12 nmol m^{-2} s^{-1} (equals to about 0.38–0.45 gC m^{-2} $year^{-1}$) under the SSP119 scenario. Reflecting on the 35 years before 2015, the VISIT model

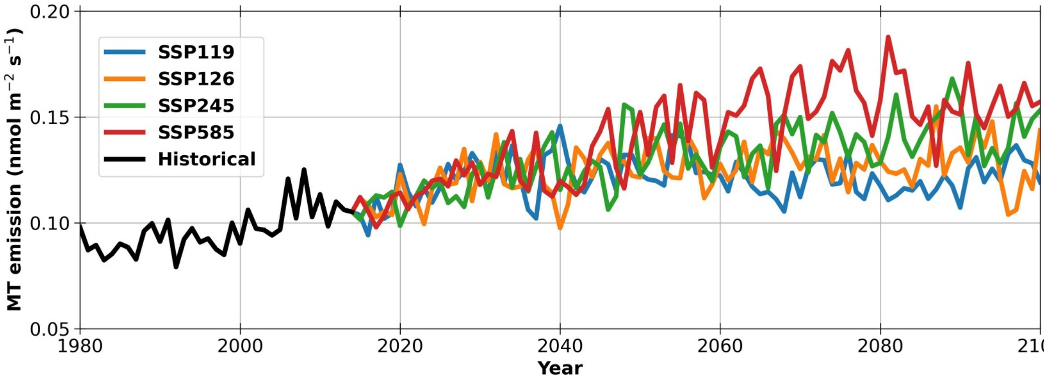

Figure 4. MIROC6-scenario-based future MT emissions at Fuji Hokuroku site simulated by the Vegetation Integrative SImulator for Trace gases model.

shows va consistent increase, reaching approximately 0.1 nmol m^{-2} s^{-1} (equals to about 0.38 gC m^{-2} $year^{-1}$) by 2015.

3.3. Relationships Between MT Emission and GPP Trend

The trends in GPP variation (Figure 5) differ markedly among the four future SSP scenarios, particularly from 2040 onward, specifically, the GPP rate is projected to reach a level of approximately 5.5 μmol C m^{-2} s^{-1} (averagely equivalent to 2,076 gC m^{-2} yr^{-1}) by 2100 under the high-emission SSP585 scenario, whereas the other three low-emission scenarios show GPP levels in the range of 3.0–4.0 μmol C m^{-2} s^{-1} (equivalent to about 1,133 to 1,512 gC m^{-2} yr^{-1}).

To connect MT emission with GPP variations in terms of short-term environment change and long-term future climate change, we analyzed the sensitivity between GPP-related environmental conditions (including temperature, photosynthetically active radiation (PAR) and CO_2 concentration) and the short-term ratio of MT and GPP in 2011 (Figure S4a in Supporting Information S1), indicating temperature have the most significant impact on determining this ratio. Compared with this, we found under long-term environmental change in SSP 585 scenario with highest CO_2 emission (Figure S4b in Supporting Information S1), the temperature, CO_2 concentration, and PAR all suggest the negative roles (Pearson correlation coefficient <0) in promoting the MT/GPP ratio, while CO_2 concentration exhibits the most pronounced inhibitory effect on the MT/GPP ratio, outweighing the relevance of temperature, which potentially reveals that CO_2 concentration will play a more pivotal role than temperature in affecting the long-term distribution of future GPP for production of MT.

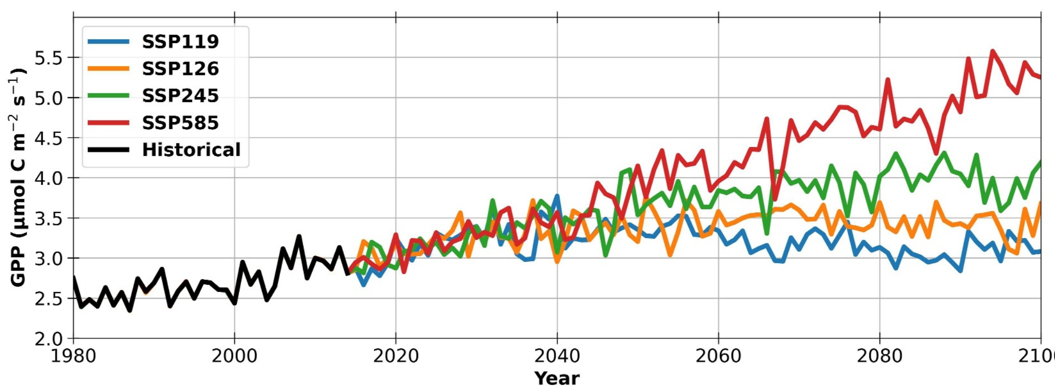

Figure 5. MIROC6-scenario-based simulations of gross primary production (GPP) using the Vegetation Integrative SImulator for Trace gases model.

4. Discussion

4.1. Prospects for Process-Based Modeling Approach

The process-based simulation approach employed by the VISIT model allows more comprehensive representation of the impacts of environmental factors on MT emission rates, including how MT is produced, stored, and emitted. Also, the comparison with MEGAN suggested that the VISIT model can explain the influence of the changes of short-term conditions from the perspective of vegetation photosynthesis on MT emission. Prior research has also supported that process-based models exhibit better performance in capturing the effects of environmental factors on ecosystem productivity and subsequent BVOC emissions (Arneth et al., 2016; Schurgers, Arneth, et al., 2009).

Our study connects the dynamic vegetation photosynthesis process with MT emission by introducing the photosynthesis process. The current simulation of terpenoid production process still relies on empirical formulas, lacking of process-based explanation on how environmental conditions work on MT production (Niinemets, Monson, et al., 2010). More processes specific processes considering enzyme activity (Grote et al., 2014) and leaf energetic status (Morfopoulos et al., 2014) are supposed to be added into model for tightening the relationship between photosynthesis and MT emission.

4.2. Model Uncertainty

In the VISIT model, we only considered the emissions of MT from major tree species (*Larix kaempferi*) at FHK site, overlooking the MT emissions from other vegetation types within this ecosystem, and the difference between the leaf-level emission capacity among species can be a source of causing model uncertainty (Ito & Inatomi, 2012). This uncertainty and the lack of soil BVOC simulation module (refer to Limitation (1) of Section 4.3 below) may become a comprehensive factor leading to the underestimation of MT simulation results in early May and late October (Figure 3a). Besides, to calculate the parameter ε (the proportion parameter transferring photon flux to terpenoid units), the VISIT model adopts output parameter (1/GPP standard conditions [leaf temperature of 30°C and a PAR of 1,000 μmol m^{-2} s^{-1}]) from the LPJ-GUESS model and assumes that the emission capacity at the leaf level equals the rate of produced MT. This introduced parameter and the assumption from the LPJ-GUESS model can also be sources of model uncertainty in the BVOC production simulation (Schurgers, Arneth, et al., 2009).

4.3. Suggestions for Future Work

To extend the current model developments to larger-scale (regional) applications, we propose addressing the following challenges: (a) The model only considers vegetation-originated BVOC emissions, while the observation data might encompass BVOC released from soil and litter, thus accounting for soil BVOC emission into the model (Tang et al., 2019) could further improve model performance; (b) The model input data of ambient temperature might not be equal to the plant leaf temperature (Seco et al., 2022). As the BVOC production algorithm principally needs leaf temperature as an input (Niinemets et al., 1999), there is still a need to bridge the gap for scaling the ambient temperature to the leaf temperature in the VISIT model; (c) The effect of water stress on emissions was not incorporated for influencing the BVOC production process in the VISIT model, but this is important for an accurate simulation of the plant suffers from possible drought conditions in future (Strada et al., 2023; H. Wang et al., 2022).

5. Conclusions

This study extended process-based BVOC simulation module into the VISIT model for dynamically simulating MT emission from a *Larix kaempferi* forest. The modeled MT production is linked to plant photosynthetic activities and the produced MT is partitioned into de novo emissions and temperature-dependent storage emissions. The modeled emissions were further evaluated with the half-hourly observations and also compared the model performance with the widely-used BVOC emission model, MEGAN. We found that the VISIT model showed better performance in terms of MBE and RMSE. Furthermore, we investigated the short-term responses of the MT/GPP ratio to temperature, CO_2 concentration, and PAR, and found its dominant determining factor is temperature. In future projection, our analysis revealed that the long-term increase in CO_2 concentration plays the most significant role in determining this value. This study accomplishes the MT simulation within the VISIT model by linking MT production with plant photosynthesis and considering MT storage, thereby providing a potential useful tool for investigating site-based BVOC simulation at high temporal resolution.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The code for the site-based VISIT model for the FHK site, and the panel data for drawing the figures are available at https://doi.org/10.5281/zenodo.11379644 (Z. Chen & Ito, 2024) and https://doi.org/10.5281/zenodo.11215992 (Z. Chen et al., 2024), respectively. The code for the MEGAN model (version 3.1) can be requested at https://bai.ess.uci.edu/megan/data-and-code (Guenther et al., 2020). The observed MT and meteorological data for the FHK site are available at https://db.cger.nies.go.jp/ged/ja/ (Mochizuki et al., 2014; Teramoto et al., 2017, 2019). The MODIS LAI data can be found at https://lpdaac.usgs.gov/products/mod15a2hv006/. The NCEP (CFSR) climate data can be acquired at https://climatedataguide.ucar.edu/climate-data (Schneider et al., 2013). The future climate data from MIROC6 can be accessed at https://h08.nies.go.jp/jpn_cdfdm/nies2020/Ver.2020/index.html (Tatebe et al., 2019).

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