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Scenario Analysis of Renewable Energy–Biodiversity Nexuses Using a Forest Landscape Model

Chihiro Haga[1]*, Marimi Maeda[1], Wataru Hotta[2], Takahiro Inoue[3], Takanori Matsui[1], Takashi Machimura[1], Masahiro Nakaoka[4], Junko Morimoto[5], Hideaki Shibata[3], Shizuka Hashimoto[6,7] and Osamu Saito[7]

[1] Division of Sustainable Energy and Environmental Engineering, Graduate School of Engineering, Osaka University, Suita, Japan, [2] Graduate School of Agriculture, Hokkaido University, Sapporo, Japan, [3] Field Science Center for Northern Biosphere, Hokkaido University, Sapporo, Japan, [4] Akkeshi Marine Station, Field Science Center for Northern Biosphere, Hokkaido University, Akkeshi, Japan, [5] Research Faculty of Agriculture, Hokkaido University, Sapporo, Japan, [6] Department of Ecosystem Studies, The University of Tokyo, Bunkyo-ku, Japan, [7] Institute for Global Environmental Strategies, Hayama, Japan

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***Correspondence:**
Chihiro Haga
chihiro.haga@ge.see.eng.osaka-u.ac.jp

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The introduction of renewable energy (RE) is essential for building a sustainable society. However, RE can cause conflicts between energy production and biodiversity conservation. This study conducted a scenario analysis to evaluate potential conflicts in the nexuses between energy and biodiversity for the Bekambeushi River watershed located in northeastern Japan. The increasing rate of pastureland abandonment resulting from a declining farmer population is a source of great uncertainty in this area. Two alternative sources of RE were selected to utilize these abandoned pasturelands, each taking a unique approach to meet targets stipulated by regional energy plans, thereby producing different ecological consequences at the landscape scale. Thirty-one RE introduction options were simulated, comprising a range of pastureland abandonment expansion speeds and ratios of solar photovoltaic (PV) plant installation to biomass energy use. These were superimposed using two IPCC representative concentration pathway (RCP) scenarios, 2.6 and 8.5, resulting in 62 scenarios that were summarized as three groups based on the RE supply–demand balance and the ecological impacts. The LANDIS-II model was used to simulate these scenarios from 2016 to 2100. The results indicate that both the rate of pastureland abandonment and the ratio of the two RE sources had a large impact on changes in tree species diversity and the habitat suitability of raptors. Abandoned pastureland converted to tree biomass energy production shifted to pioneer species-dominated forest. The plant species composition of transitional forests varied between the climate scenarios. The higher temperature of the RCP 8.5 scenario toward 2100 prevented the establishment of *Betula platyphylla* and altered tree species diversity and the habitat suitability of *Ketupa blakistoni blakistoni*. Biomass energy utilization produced less energy than the demand but increased the three ecological indicators. Solar PV systems provided more energy than the regional demand, but the tree diversity and habitat suitability indices for two raptors declined. However, an appropriate mixture of the two RE sources satisfied the regional energy demand and maintained ecological conditions. Our results suggest that land–energy planning should consider energy–biodiversity nexuses to strike a balance between decarbonization and biodiversity conservation.

Keywords: climate change, renewable energy mix, farmland abandonment, solar power generation, woody biomass energy, LANDIS-II

INTRODUCTION

Building a decarbonized society has become a key global concern (UNFCCC, 2015). Currently, 186 parties have submitted a nationally determined contribution (NDC) aimed at limiting global warming to 1.5–2°C (UNFCCC, 2019). Japan's NDC pledged to reduce CO_2 emissions by 80% by 2050 (Cabinet Office, Government of Japan, 2016). In Japan, 86.3% of greenhouse gas emissions in 2016 were CO_2 from the energy sector (Ministry of the Environment, Japan [MOE], 2019a), and the government is planning to shift to a decarbonized energy supply system (Ministry of the Environment, Japan [MOE], 2018, 2019b). However, the *Special Report on Global Warming of* 1.5°C (IPCC, 2018) suggested that the emission pathway reflecting the current NDCs will raise the global mean temperature by 3°C. Therefore, against the current situation, transformative changes in social systems are required to build a sustainable society (IPCC, 2018; IPBES, 2019).

Promoting the introduction of renewable energy (RE) plays a key role in reducing greenhouse gas emissions (IPCC, 2014), but its introduction could impose a burden on ecosystems, such as land use change during construction and maintenance during operation (Abbasi and Abbasi, 2000; Field et al., 2008; Gasparatos et al., 2017; Gibson et al., 2017). The IPBES also indicated the need for careful consideration of ecosystems when introducing RE (IPBES, 2019). The introduction of RE is related to the UN's Sustainable Development Goals (SDGs): Goal 7: Affordable and clean energy, Goal 13: Climate action, and Goal 15: Life on land (United Nations, 2015). Therefore, toward developing a post-2020 biodiversity framework, RE utilization constructed in harmony with nature is essential for building a sustainable society.

Previous global-scale studies have demonstrated trade-offs between biodiversity conservation and climate change mitigation, including the introduction of RE (de Vries et al., 2007; Santangeli et al., 2016a; Palomo et al., 2019). Santangeli et al. (2016b) identified the overlap of biodiversity conservation areas with high potential for crop, solar photovoltaic (PV), and wind energy production to identify areas that have a low impact on biodiversity. Harper et al. (2018) pointed out that the land use conversions of carbon-rich forests for energy crop production to mitigate climate change would reduce the total amount of carbon fixation by coupling an integrated assessment model (IAM) and a dynamic global vegetation model or DGVM. Ohashi et al. (2019) predicted changes in the habitats of 8,428 species using a species distribution model based on future land use under Shared Socioeconomic Pathways (SSPs) scenarios reflecting climate change mitigation measures calculated using an IAM and stated that habitat reduction due to climate change is greater than land use conversion under mitigation measures.

Local-scale studies have also indicated potential conflicts between the introduction of RE and biodiversity (Kienast et al., 2017). Tarr et al. (2017) calculated the future habitat suitability of 16 wildlife species under biomass energy harvesting scenarios using a spatially explicit state-and-transition model. Tarr et al. (2017) stated that bioenergy policies will cause trade-offs between species that require different ecological niches. Hori et al. (2016) and Hori et al. (2019) optimized the RE mix at a local scale by focusing on solar, hydro, wind, geothermal, and biomass resources and visualized trade-offs six indicators: the proportion of developed RE, economic balance between initial installation costs and returns from RE production, decrease in CO_2 emissions, circulation rate of biomass resource in a region, RE diversity, and area of potentially impacted ecosystem. Moore-O'Leary et al. (2017) described relationships between land, energy, and ecosystems as nexuses that invoke such trade-offs. The types and amount of RE sources are spatially distributed heterogeneously (Pogson et al., 2013), and the environmental impacts of RE utilization differ among RE sources (Abbasi and Abbasi, 2000; Gibson et al., 2017). Therefore, climate change mitigation plans need to be developed considering the nexuses between local RE resources and biodiversity conservation.

Quantitative models can effectively evaluate the impact of RE on ecosystems (Laranjeiro et al., 2018; Raoux et al., 2018). Future climate change will also affect local ecosystem conditions and alter the supply potentials of various ecosystem services (Cantarello et al., 2017). Most studies dealing with conflicts between the introduction of RE and biodiversity have only focused on changes in land use and land cover classes as state spaces of the Markov process (Costanza et al., 2015; Duden et al., 2017; Tarr et al., 2017). However, process-based models that simulate the climate change response of vegetation will provide robust and informative scientific suggestions (Gustafson et al., 2015; Keane et al., 2015) for maintaining future energy–biodiversity nexuses to local stakeholders.

A FLM is a process-based dynamic simulation model of vegetation succession at a landscape scale under future climate change (Xi et al., 2009; Shifley et al., 2017). Previous studies have applied FLMs to quantify the effects of human and natural disturbances, such as vegetation change caused by economic growth (Ward et al., 2005; Thompson et al., 2016; Duveneck and Thompson, 2019) and from a shrinking society (Haga et al., 2018; Sil et al., 2019). FLMs have also been used to simulate the impacts of aboveground and deadwood biomass harvesting for fuels on ecosystem services and the quality of wildlife habitats (see, for example, Creutzburg et al., 2016; Thompson et al., 2016; Hof et al., 2018).

Future social scenario narratives in the fields of both climate change and biodiversity and ecosystem services do not specify ecosystem management activities under decarbonization requirements at local scales (Millennium Ecosystem Assessment [MA], 2005; O'Neill et al., 2014). Therefore, the purpose of this study was to explore future scenarios that strike a balance between the introduction of RE and biodiversity conservation under changing climate and societal conditions using a process-based forest landscape model (FLM). The specific objectives were to (1) simulate ecosystem impacts and expected energy supply under mixed RE energy installation scenarios, (2) identify the RE–biodiversity nexuses in a local basin, and (3) explore the scenarios to meet both RE utilization and biodiversity conservation.

MATERIALS AND METHODS

We simulated vegetation succession under different land use scenarios and evaluated energy supply potential, ecosystem services, and ecological impacts using an FLM.

Study Area Description

The Bekambeushi River watershed in northeastern Japan, where RE introduction plans, such as woody biomass (Akkeshi town, 2018a) and a solar PV plant (Nikkei XTECH, 2018), are underway, was selected as the case study area (**Figure 1A**). The total area of the watershed is 700 km^2, with a small difference in elevation (maximum elevation = 141 m) (**Figure 1B**; Geosptial Information Authority of Japan [GSI], 2019). The forest and pastureland soils consist of Andosols (Obara et al., 2016). The current monthly mean air temperature ranges from −8 to 20°C and annual precipitation is 1200 mm (Esgf-CoG, 2017). In particular, changes in temperature are concerned, with the mean air temperature increase 1.4–5.0°C by 2100 under RCP scenarios (Esgf-CoG, 2017). Forests and pasture lands cover 70 and 20% of the watershed, respectively (**Figure 1C**; Biodiversity Center of Japan, 2017). The Bekambeushi River wetland was listed in the Ramsar Convention in 1993 (Akkeshi town, 2019a). In the national forest in the northern areas, the dominant species is *Larix kaempferi* (Lamb.) Carrière. In the private forest in the southern areas, the dominant species are Sakhalin fir [*Abies sachalinensis* (F. Schmid)] Mast.] and a mixed forest of Sakhalin fir and Japanese oak (*Quercus crispula* Blume). In this study area, deer browsing damages to agriculture and forestry are the major natural disturbances, and local government are working to capture them (Akkeshi town, 2018c).

The main industries are fisheries and aquaculture in Akkeshi Bay, Lake Akkeshi, and the offshore area; forestry in the national and private forests; and dairy farming (Akkeshi town, 2018b), but the rapid decline in primary industries is of major concern in the region. The total residential population in the watershed was 8,604 in 2010 and is projected to be 4,980 by 2050 (National Land Numerical Information [NLNI], 2017). The area of the clear-cutting and thinning of larch and Sakhalin fir for timber and pulp production has declined in recent years (Hokkaido Prefecture, 2019). The region's administrative documents reflect concern that the abandonment of pastureland will increase because of the declining population (Akkeshi town, 2019b). This decline is a baseline trend in Japan (National Institute of Population and Social Security Research [NIPSSR], 2018; Saito et al., 2018), especially in rural areas (Matsui et al., 2019).

Model Description

In this study, the LANDIS-II model, version 7.0 (Scheller et al., 2007), a widely applied FLM, was used to simulate the ecological impact of the introduction of RE. LANDIS-II is a modeling platform comprising a suite of extensions to simulate various establishment, growth, and disturbance processes. This modeling platform currently attempts to integrate growth and material cycles by referring to mechanistic models, such as the CENTURY soil organic matter model and PnET-II to expand its applicability to robust climate change impact assessment (Scheller et al., 2011; de Bruijn et al., 2014). The model computes vegetation succession at landscape scales by representing landscapes as grid cells. The state of vegetation in each grid cell is represented as a species–age cohort.

The Net Ecosystem Carbon and Nitrogen (NECN) Succession version 6.3 (Scheller et al., 2011), was used to simulate vegetation dynamics under climate change. The extension computes cohort establishment and biomass growth as functions of the environmental condition. The probability of establishment for each grid cell for each species is defined by a function of the minimum January temperature, soil and water, growing degree days (GDD), and light availability. The biomass growth is calculated as the balance between monthly net primary productivity (NPP) and mortality. The monthly NPP was computed by multiplying the monthly maximum NPP by the environmental limits in a grid cell: monthly mean temperature, plant-available soil N, the water and light availability, and density effects. Species and functional group parameters were determined in reference to Haga et al. (2018) and the default value of the CENTURY soil organic matter model (see **Supplementary Material 1**). We calibrated the NECN succession extension by comparing the simulated and observed aboveground biomass (AGB) growth and litterfall (see **Supplementary Material 2**).

Settings for the Introduction of Renewable Energy Scenarios

In a shrinking society, there are great uncertainties around the presence of unused land and how to use it (Shoyama et al., 2018). Therefore, we designed 31 scenarios of land use and RE introduction from 2016 to 2100 comprising varied speeds of pastureland abandonment expansion and ratios of solar PV plant installation to biomass energy use (**Table 1**). First, six scenarios for pastureland abandonment expansion speed were set (**Table 1**). The lowest speed scenario was 0 ha year^{-1}, maintaining all pastureland to 2100. In the highest speed scenario, we assumed that pastureland would be abandoned at the same speed of population decline. Therefore, the area of abandoned pastureland increased to 42% of the current pastureland in 2050 according to

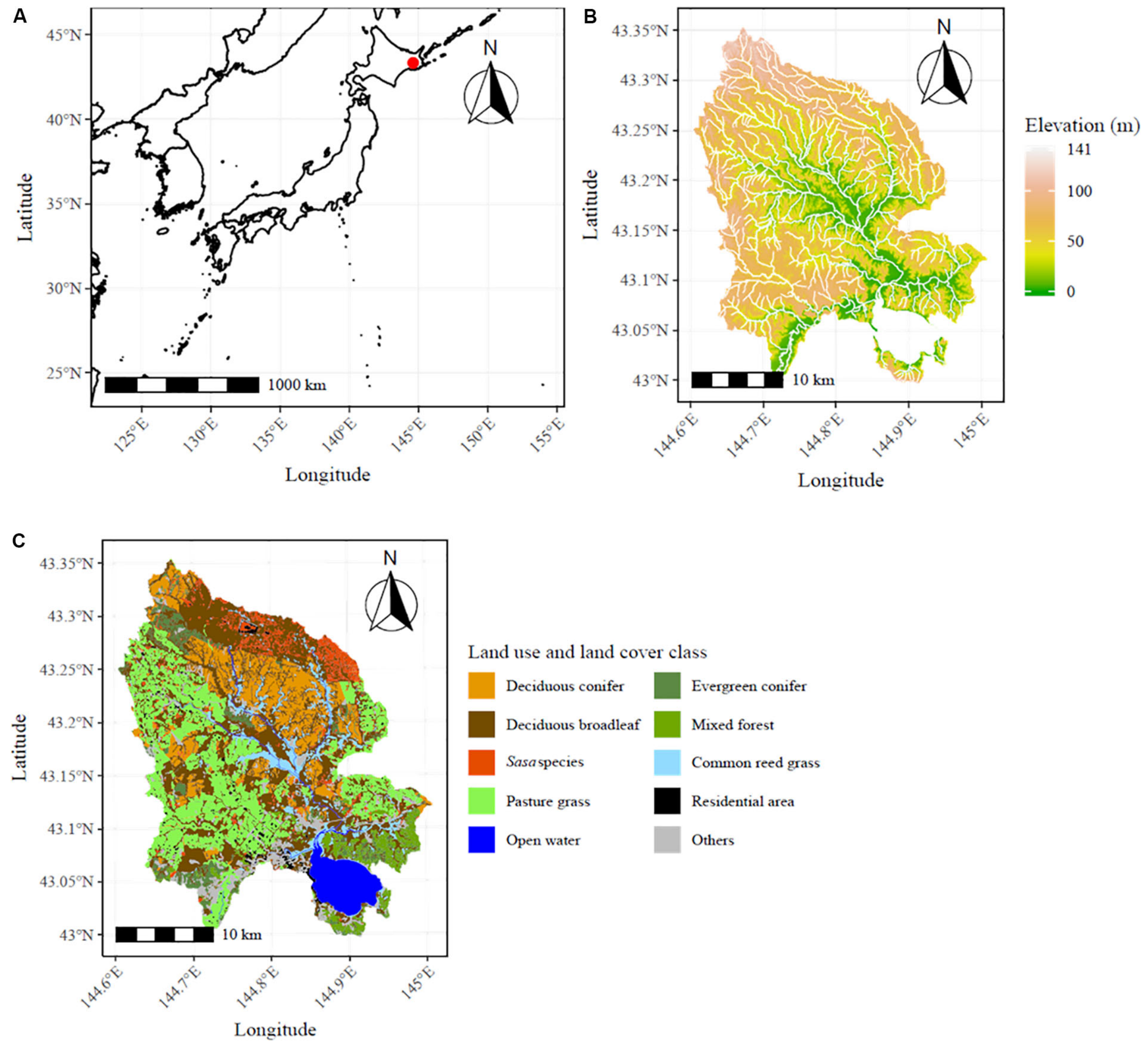

FIGURE 1 | Description of the study area. **(A)** The location of the Bekambeushi River watershed (red dot), **(B)** the digital elevation model and distribution of rivers (white lines), and **(C)** the vegetation distribution.

a population decline of 58%. The other four scenarios were set at equal intervals between 0 and 223 ha year^{-1} (**Table 1**).

For each pastureland abandonment scenario, the locations of the abandoned pastureland were determined using a *Manageability* index that considered the multiple socio-geographical conditions of each grid cell. The index assumes that a grid cell with a lower population in the nearest residential area, a farther the distance to the residential area and the nearest road, a larger slope, higher elevation, and the smaller the pastureland patch area, the lower the *Manageability* (Haga et al., 2018; Kobayashi and Nakamura, 2018). Pastureland grid cells with lower *Manageability* were abandoned first. *Manageability* was calculated as follows:

$$Manageability_i = \frac{pop_i}{distToResi_i} \times \frac{1}{distToRoad_i} \times \frac{1}{meaSlope_i} \times \frac{1}{meaElev_i} \times patchArea_i \quad (1)$$

where $Manageability_i$ is the manageability of grid cell i; pop_i; and $distToResi_i$ are the population and the distance to the nearest residential grid cell in 2050 from the grid cell i (m), respectively (National Land Numerical Information [NLNI], 2017); and $distToRoad_i$is the distance to the nearest road from the grid cell i (m). $meaSlope_i$ and $meaElev_i$ denote the mean slope (degree) and elevation (m) of grid cell$i$, respectively. $patchArea_i$ is the area of the pastureland patch in which the grid cell i belongs (m^2).

The following two types of abandoned pastureland were excluded from any RE introduction: abandoned pastureland (1) within 300 m of a river or (2) with a wetland history. The former was to conserve riparian forest, which is an ecologically and culturally important ecosystem (Nakaoka et al., 2018), and the latter was because the pastureland has the potential to become wetland (Morimoto et al., 2017). Wetland history was identified using a 1920s historical topographical map (Kaneko et al., 2008).

TABLE 1 | Pastureland management and renewable energy introduction scenarios.

	Scenarios
Annual pastureland abandonment expansion speed (ha year^{-1})	A0: All pastureland will be managed
	A45: 45 ha year^{-1}
	A89: 89 ha year^{-1}
	A134: 134 ha year^{-1}
	A178: 178 ha year^{-1}
	A223: 223 ha year^{-1}
Solar photovoltaic (PV) plant installation and biomass energy use mix	S0.0: No solar PV plant installation
	S0.2: 20% of abandoned pastureland used for solar PV plant installation
	S0.4: 40%
	S0.6: 60%
	S0.8: 80%
	S1.0: 100%

TABLE 2 | List of simulated species.

Common names	Scientific names
Japanese white birch	*Betula platyphylla* Sukaczev var. japonica (Miq.) H. Hara
Japanese ash	*Fraxinus mandshurica* Rupr.
Japanese oak	*Quercus crispula* Blume
Japanese elm	*Ulmus davidiana* Planch. var. japonica (Rehder) Nakai
Japanese alder	*Alnus japonica* (Thunb.) Steud.
Larch	*Larix kaempferi* (Lamb.) Carrière
Sakhalin fir	*Abies sachalinensis* (F. Schmidt) Mast.
Pasture grass	–
Sasa species	–

Abandoned pastureland was categorized as two types of land use according to the distance to the nearest forest for each year: land for producing solar energy and land for obtaining woody biomass energy. This allocation was based on the development policy that solar PV plants are initially installed on abandoned pastureland far away from forests to minimize impacts on wildlife, with the balance of the abandoned pastureland used for biomass energy production. Six ratios were used to represent the mixture of solar PV plants and woody biomass energy scenarios (**Table 1**).

The AGB of all tree species in the abandoned pastureland used for biomass energy production was harvested. Under the current climate condition, Japanese white birch (*Betula platyphylla* Sukaczev var. japonica) is the representative regional pioneer species expected to establish on the abandoned pastureland. Therefore, we clear-cut all the tree species in the abandoned pastureland for biomass energy production where it contained 25-year-old Japanese white birch, the maximum growth period. No species were planted after the clear-cutting because natural regeneration was expected. On the abandoned pastureland used for solar PV plants, all the grass and tree species were removed every year for the maintenance of the solar PV panels.

Simulation Settings Common for All Scenarios

The NECN succession extension requires spatially explicit initial conditions for both the age and AGB for each plant species. We created an initial tree species distribution at 100 m resolution. Plant species distribution was obtained from a vegetation map that recorded community names (Biodiversity Center of Japan, 2017). The dominant plant communities, which cover 95% of the watershed, were selected for the simulation (**Supplementary Table 4**), and seven tree species and two grass species were selected as a result (**Table 2**). The initial age and AGB were set according to the forest registers of the national, prefectural, and private forests (Hokkaido Prefecture, 2017a,b; Ministry of Agriculture Forestry and Fisheries [MAFF], 2017). Soil organic matter (SOM) content, soil depth and properties related to soil carbon and water dynamics were determined uniformly for each forest and pasture from the literature (Hokkaido National Agricultural Experiment Station, 1983). The decomposition rates of SOM were set according to the calibration criteria proposed in the previous study (Lucash et al., 2019).

The Biomass Harvest extension, version 4.3, was used to apply the same forest management practice to all scenarios referring to the regional standard plan (Akkeshi town, 2017; Hokkaido Prefecture, 2017c; **Supplementary Table 4**). The target species were larch, Sakhalin fir, and Japanese oak. In the timber production forest, the target species were clear-cut and replanted. In the conservation area, such as the riparian forest, selective cutting and planting of the target species were conducted. Thinning was applied to cohorts that reached the thinning age used as standard practice in this area (Akkeshi town, 2017; Hokkaido Prefecture, 2017c).

Representative concentration pathway (RCP) 2.6 and 8.5 scenarios (IPCC, 2013) calculated by the MRI-CGCM3 model (Esgf-CoG, 2017) were selected as the climate data to evaluate uncertainty corresponding to climate change. To correct for bias between the MRI-CGCM3 data and the observations, monthly mean temperature and monthly precipitation offsets were determined by comparing data from the model and the Ota Meteorological Observatory (Japan Meteorological Agency, 2018; **Supplementary Table 5**). In total, 62 simulations, a combination of the 31 RE introduction scenarios and the two climate scenarios were conducted from 2016 to 2100.

Evaluation Indicators

Renewable energy production and three ecological indicators were evaluated as follows using the simulated land use and land cover (LULC) changes, AGB, and harvested biomass. R, version 3.6.3 (R Core Team, 2019) was used for the analysis.

Renewable Energy Supply

The amount of RE supply was estimated as heat energy. First, the heat energy obtained by burning the woody biomass (TJ year^{-1}) was calculated (Tatebayashi et al., 2015) by assuming that all harvested AGB (oven-dry kg biomass year^{-1}) obtained from the abandoned pastureland and forest thinning was used for pellets. The moisture content, yield rate, and lower calorific value were set to 10, 80%, and 16.0 MJ kg^{-1} (Japan Wood Pellet Association, 2017). Harvested biomass is storable, so a 5 years moving average was used to evaluate the expected amount of heat energy per year.

Second, the amount of the electrical energy generated by the solar PV plants was calculated by multiplying the total area of the solar PV plants per year (m^2) with a basic unit of annual power generation. We used 61.58 kWh m^{-2} $year^{-1}$ as the basic unit, as used in a previous RE estimation procedure (Ministry of the Environment, Japan [MOE], 2010). This generated electrical energy was then converted to heat energy (TJ $year^{-1}$) by multiplying with a conversion unit of 3.6×10^6.

Ecological Impacts

Three ecological indicators were evaluated: plant species diversity and two habitat suitability indices (HSI), the mountain hawk-eagle (*Spizaetus nipalensis orientalis*) and the Blakiston's fish owl (*Ketupa blakistoni blakistoni*).

The Shannon–Wiener diversity indices for the plant species were calculated using the simulated AGB for each grid cell. Abandoned pastureland converted to solar PV plants was regarded as a zero diversity index. Abandoned pastureland with a wetland history was also set to zero because the land was excluded from the LANDIS-II simulation.

We calculated the habitat suitability indices for the mountain hawk-eagle and the Blakiston's fish owl, which have different ecological niches, as representative species affected by the land use changes. The mountain hawk-eagle is a raptorial bird, 70–80 cm in length, that lives in steeply sloping mountain forests (Ministry of the Environment, Japan [MOE], 2012). The eagle uses mature forests and forest edges to prey on small to medium reptiles, birds, and mammals living in the forest (Ministry of the Environment, Japan [MOE], 2012). A habitat suitability index for the mountain hawk-eagle was calculated with a 1 km resolution using the following (Itoh et al., 2012):

$$\log \frac{p_s}{1-p_s} = -12.7853 + 0.0018 \times X_1 + 0.0987 \times X_2 + 0.1071 \times X_3 + 0.0879 \times X_4 + 0.0851 \times X_5 + 0.0001 \times X_6 \quad (2)$$

where p_s is the habitat suitability index for the mountain hawk-eagle for each 1 km grid cell; X_1 and X_2 are the mean elevation (m) and slope (degree) of the grid cell, respectively; X_3 is the occupancy of the broadleaf forest and mixed forest area of the grid cell; X_4 is the occupancy of the plantation *Cryptomeria japonica* (L.f.) D. Don and *Chamaecyparis obtusa* (Siebold et Zucc.) Endl. of the grid cell; X_5 is the occupancy of open area suitable for foraging activities in the grid cell; and X_6 is the length of forest edge (m) between the open area and forests in the grid cell. For X_3, if the AGB of the broadleaf species occupy more than 30% of the total AGB for each 1 km grid, the grid was identified as broadleaf and mixed forest. X_4 was set to zero for all grids because these tree species are not distributed in the study area. Pastureland, grassland, and wetland were regarded as open areas for X_5 and X_6. A previous study reported that solar PV plants contribute to increases in the populations of small grassland birds (Kitazawa et al., 2019). However, because there is concern that the feeding behavior of raptors could be hindered by solar PV plants (Walston et al., 2016), we excluded the solar PV plants.

The Blakiston's fish owl is a nocturnal raptor with a total length of ~70 cm. In 2018, the owls were only living in Hokkaido, Japan, and are classified as a critically endangered species (Ministry of the Environment, Japan [MOE], 2019c). This owl preys mainly on fish and amphibians and normally nests in tree cavities in riparian forests (Yoshii et al., 2018), however, successful cases of nesting in artificially installed nest boxes have been confirmed (Takenaka, 2018). Therefore, habitat suitability for the Blakiston's fish owl was calculated for each grid with a 4 km resolution using the following (Yoshii et al., 2018):

$$\log \frac{p_k}{1-p_k} = -23.36 + 9.32 \times 10^{-3} \times Y_1 + 5.026 \times log\left(Y_2+1\right) - 0.326 \times \left\{log\left(Y_2+1\right)\right\}^2 \quad (3)$$

where p_k is the habitat suitability index for the owl for each 4 km grid cell, Y_1 is the total area (m^2) of riparian natural forest within 300 m of rivers (National Land Numerical Information [NLNI], 2009) for each grid cell, and Y_2 is the total length (m) of rivers for each grid cell. The current species composition in natural forests in this region is *Abies sachalinensis*, *Abies sachalinensis-Quercus crispula*, *Ulmus davidiana*, *Alnus japonica*, and *Alnus japonica-Fraxinus mandshurica* communities (Biodiversity Center of Japan, 2017). If riparian forests within 300 m of rivers consisted of these species and had not been either clear-cut or planted, we categorized them as natural forests. Regular maintenance activities for solar PV systems near riparian forests may diminish the breeding success of the owl; therefore, we excluded riparian natural forests within 300 m of solar PV plants in the calculation (Takenaka, 2018).

Finally, 62 scenarios were summarized into three groups by referring to the balance between the mean RE production from 2090 to 2100 and the total energy demand of the area in 2010. We evaluated the relative ecological impacts of land use change, RE introduction, and climate change for each scenario by comparing mean values from 2090 to 2100 for the three ecological indicators.

RESULTS

Changes in LULC and Aboveground Biomass

In the A0 scenario, which maintains all pastureland, the changes in both LULC and AGB differed between the RCP scenarios (**Figure 2**). However, Japanese white birch forest shifted to the other broadleaf forests regardless of the RCP scenario, but this trend was accelerated in the RCP 8.5 scenario (**Figure 2A**). The birch forest declined from 137 to 26 km^2 in 2100 and shifted to Japanese alder after 2050 in the RCP 8.5 scenario (**Figure 2A** and **Supplementary Table 6**). The total changes, including both an increase and a decrease in area, were the highest among the pioneer species, such as the Japanese birch and Japanese alder, and the target forestry species, such as larch and Sakhalin fir (**Figure 2A**; total change in **Supplementary Table 6**). These two pioneer species and the larch forest shifted to the other

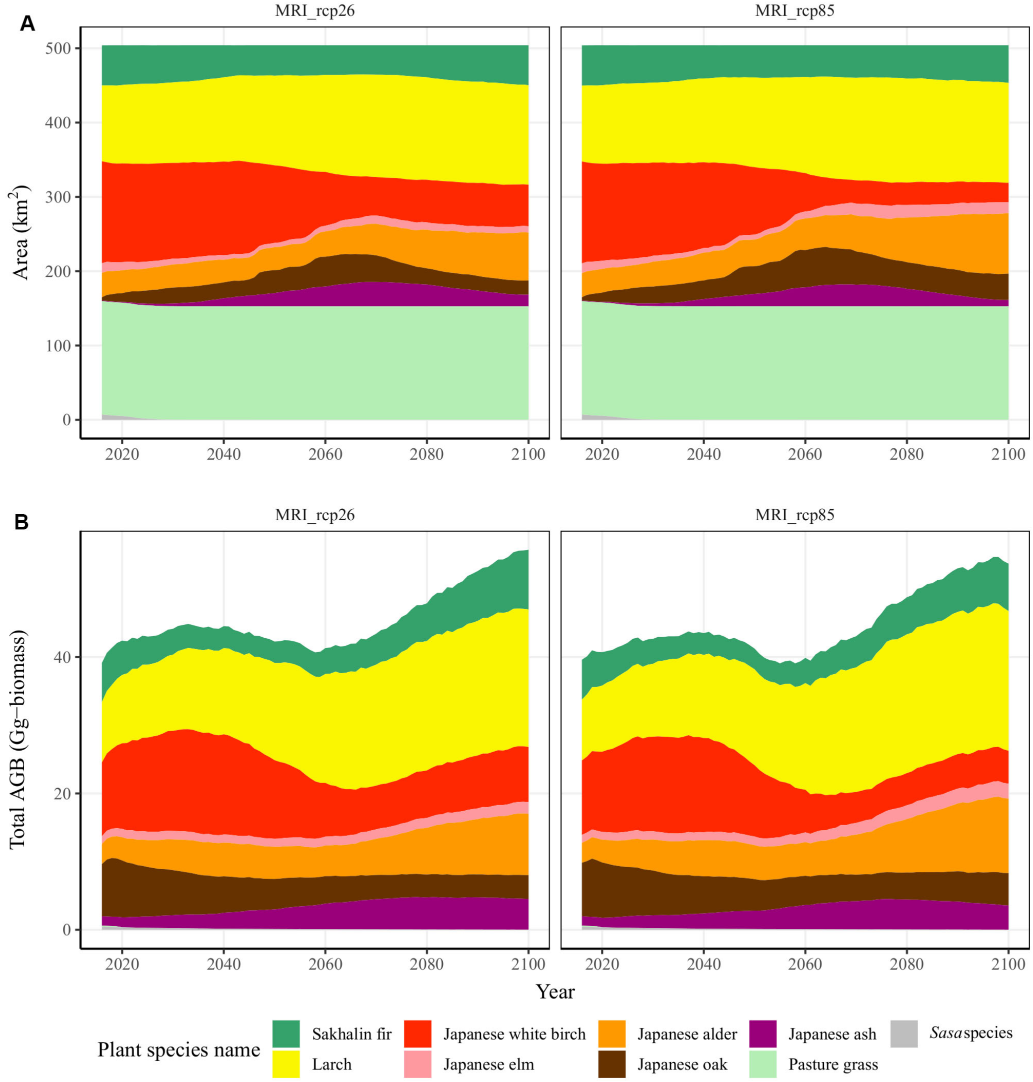

FIGURE 2 | Changes in the **(A)** land use and land cover and **(B)** the total aboveground biomass (AGB) for the scenario with no pastureland abandonment expansion (A0) for two climate scenarios (left = IPCC RCP 2.6 and right = IPCC RCP 8.5). The colors indicate the nine plant species simulated in this study.

species (net change in **Supplementary Table 6**). The total area of Sakhalin fir forest was maintained (**Supplementary Table 6**). With an increasing area of alder forest, the total AGB within the watershed reached 55.8 and 53.7 Gg biomass in the RCP 2.6 and 8.5 scenarios, respectively (**Figure 2B**). In the RCP 8.5 scenario, the AGB of Sakhalin fir, Japanese alder, and Japanese ash declined by 20–40%, and the AGB of Japanese white birch and Japanese oak increased by 22–36% (**Figure 2B**).

In the RE introduction scenarios, the abandoned pastureland was shifted to broadleaf forests and wetlands or converted to solar PV plants (**Supplementary Figures 7A,B**). In the 1920s, 8% of the pastureland was wetland, and these converted pasturelands were returned to wetlands after being abandoned. In the abandoned pastureland converted to tree biomass energy production, pioneer species, such as Japanese white birch and Japanese alder, were established. Like the changes in the forests, the AGB of alder increased toward 2100 in the RCP 8.5 scenario (**Supplementary Figures 7A,B**). In the riparian forest, especially, the total AGB increased up to 3 and 5 Gg biomass with increasing Japanese alder in the RCP 2.6 and 8.5 scenarios, respectively. In the abandoned pastureland used for tree biomass energy production, Japanese white birch declined in the RCP 8.5 scenario, and thus, the total AGB in 2100 was 15 and 13 Gg biomass in the RCP 2.6 and 8.5 scenarios, respectively.

The distribution of Japanese white birch and Japanese alder in Japan ranges between 958–2,598 and 1,066–2,842 degrees in annual GDD, respectively (5°C base threshold). The Japanese alder is thus distributed in a warmer environment than the Japanese white birch (Forestry Agency of Japan, 2019; National Land Numerical Information [NLNI], 2012). The Japanese white birch is the representative pioneer plant species in this region under the current climate (Resco de Dios et al., 2005). In the RCP

2.6 scenario, the Japanese white birch successfully established on abandoned pastureland until 2100 because the temperature changes were relatively small (**Figure 2** and **Supplementary Figures 5, 9**). However, only the Japanese alder had the potential to establish because the mean annual temperature rose by 5°C in 2100 in the RCP 8.5 scenario compared with the current climate (**Figure 2** and **Supplementary Figures 5, 9**).

Ecological Impacts

Figure 3 shows the trends of the three ecological indicators and the RE supply for each scenario.

In the no pastureland abandonment scenario (A0), selective cutting and planting of broadleaf species increased the Shannon–Wiener diversity index, increasing the mean value within the watershed from 0.04 to 0.08 toward 2100 (**Figure 3**). After 2060, the diversity index decreased due to the increased occupancy of Japanese alder. The same trend was observed for the A45–A223 scenarios. In the faster pastureland-abandonment expansion speed scenarios, the diversity index linearly increased with the expansion of secondary forest established on the abandoned pastureland. The introduction of solar PV plants decreased the diversity index compared with the same expansion speed scenarios. In the RCP 8.5 scenario, higher temperatures increased the AGB of Japanese alder, and the diversity index was lower than for the RCP 2.6 scenario.

Without pastureland abandonment, the habitat suitability index for the mountain hawk-eagle increased toward 2030 and then decreased to 0.03 by the end of this century because the area of broadleaf forest and mixed forest decreased due to the increase in larch and Sakhalin fir biomass (**Figure 3** and **Supplementary Figure 8**). In the scenarios that used abandoned pastureland to supply only woody biomass (S0.0), the HSI_s increased with increasing pastureland abandonment expansion speed. The A223-S0.0 scenario resulted in the highest HSI (0.04) among the RE introduction scenarios in 2100. The HSI decreased with the introduction of solar PV plants compared with scenarios with the same abandonment rate, and the difference in index values between the RCP scenarios was the smallest among the ecological indicators (**Figure 3**).

The mean of the HSI for the Blakiston's fish owl (i.e., HSI_k) increased from 0.07 to 0.12 toward 2100 in the A0 scenario (**Figure 3**). In the A45–A223 scenarios, the riparian forest area increased with the expansion of pastureland abandonment and the mean value increased (**Figure 3**). The higher temperature of the RCP 8.5 scenario increased the AGB of Japanese alder, categorized as natural forest, within 300 m of rivers (**Supplementary Figure 7B**). The mean HSI value for the owl thus increased, especially, in the RCP 8.5 scenario, however, the greater introduction of solar PV plants increased the area of riparian forests adjacent to the solar panels (**Supplementary Figure 8**), decreasing the index value (**Figure 3**).

Renewable Energy Production

The total RE supply in 2100 varied from 3.6×10^{-1} PJ in the A0 scenario to 1.3×10 PJ in the A223-S1.0 scenario (**Figure 3** and **Supplementary Table 10**). Tree biomass harvesting from abandoned pastureland emerged around 2040. The amount of harvested AGB fluctuated yearly because the spatial distribution of AGB from abandoned pastureland was affected by seed dispersal from surrounding forests. The amount of energy provided by solar PV plants increased in proportion to the expansion of abandoned pastureland.

Features of the 62 Scenarios

The total energy demand in this watershed was 1.3 PJ in 2010 (Hori et al., 2016). As shown in **Figure 3**, RE introduction scenarios had the potential to supply 28–998% of the regional energy demand. The 62 scenarios were thus classified into three scenarios: scenario 1, where energy production was less than the energy demand ($N = 14$); scenario 2, where RE production satisfied the energy demand and was less than five times the demand ($N = 29$); and scenario 3, where RE production satisfied the energy demand and was more than five times the RE demand ($N = 19$) (**Figure 4** and **Supplementary Table 10**).

Group 1 included the scenarios where the solar PV mixture rate was zero (S0.0) and the A45-S0.2 scenario where the area of abandoned pastureland was small and the number of installed solar PV plants was low (**Figure 4** and **Supplementary Table 10**). The amount of RE supply ranged from 3.6×10^{-1} PJ in the A0-S0.0 scenario to 1.3 PJ in the A45-S0.2 scenario (**Figure 3**). In group 1, all three ecological indicators around 2100 were higher than for the A0 scenario (**Figure 4**). In group 2, scenarios with a lower solar PV plant fraction (S0.2) maintained the three ecological indicators, whereas the higher fraction (S0.4-1.0) diminished the HSI of the mountain hawk-eagle (**Figure 4** and **Supplementary Table 10**). The habitat suitability of the Blakiston's fish owl also declined with increasing solar PV plant fraction but was higher than that of the A0 scenario (**Figure 4** and **Supplementary Table 10**). In group 3, the solar PV plant fractions for all scenarios were greater than 60% (**Figure 4**). The HSI for the mountain hawk-eagle was lower than for the A0 scenario in all scenarios in group 3 (**Figure 4**). Scenarios that relied on only solar PV plants demonstrated a greater decline in the HSI for the Blakiston's fish owl than for the A0 scenario (**Supplementary Table 10**).

DISCUSSION

This study simulated a vegetation succession by considering multiple disturbances, climate change, pastureland abandonment, and two types of RE introduction and visualized the impact on plant species diversity and the habitat suitability of two raptorial birds. The following sections identify the nexuses among these disturbances and the vegetation and wildlife habitat quality and discuss the ecosystem management required to strike a balance between RE introduction and biodiversity conservation.

Climate–Vegetation–Habitat Quality Nexus on Abandoned Pasturelands

The differences in both the establishment probability and seed dispersal ability of the two pioneer species affected the

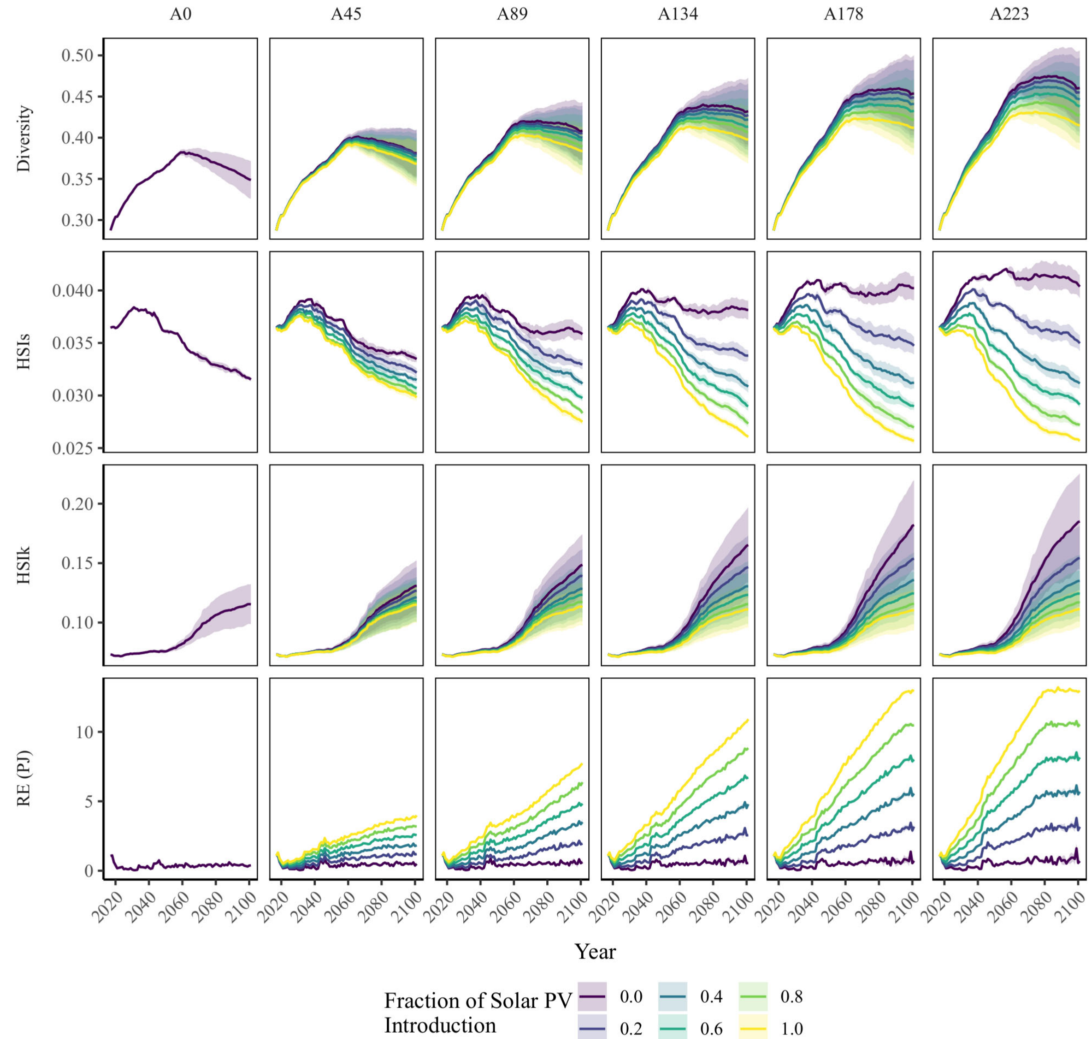

FIGURE 3 | IPCC RCP 2.6 and 8.5 scenarios for the three ecological indicators and renewable energy (RE) production potential from 2016 to 2100 for the 62 scenarios. Each line represents the mean between the two RCP scenarios, and the difference between the scenarios is represented by shading. A0–A223 represent the pastureland abandonment expansion speed, and the colors indicate the solar PV plant fraction (**Table 1**). Diversity = Shannon–Wiener diversity index, HSI_S = habitat suitability index for the mountain hawk-eagle (*Spizaetus nipalensis orientalis*), HSI_K = habitat suitability index for Blakiston's fish owl (*Ketupa blakistoni blakistoni*), and RE = the total renewable energy supply from tree biomass utilization and solar PV plants.

total AGB of Japanese alder from 2050 as the difference in temperatures between the two climatic scenarios became larger (**Supplementary Figure 5**) and created trade-offs between the plant species diversity indices, the HSI for the Blakiston's fish owl, and the total biomass of the abandoned pastureland (**Figure 2**). On the abandoned pasturelands converted for biomass energy production, the Japanese alder biomass also increased in the RCP 8.5 scenario, but the total biomass was lower than for the RCP 2.6 scenario (**Supplementary Figure 7A**). In these abandoned pasturelands, it became harder for seeds supplied by the Japanese birch that had been distributed near the pasturelands to establish, resulting in a decrease in total biomass (**Supplementary Figure 7A**). Previous studies have estimated the potential habitat of broadleaf tree species in eastern Asia under future climate change using species distribution models (see, for example, Tanaka et al., 2012; Nakao et al., 2013). To understand nexus among climate change and biodiversity, our results further demonstrate the need to model climate change impacts on multiple species dynamics considering species traits, distribution ability, and spatial distributions of plant species at finer scales.

Previous studies have shown that the effects of climate change become more significant and uncertain toward the end of this century (Lucash et al., 2019; Ohashi et al., 2019), and our results are also consistent with this finding (**Figure 3**). Moreover, pioneer species dynamics were dominant in this study, suggesting the need for longer-term simulations beyond 2100. Although governments and international organizations often develop future social scenario narratives for toward 2030 or

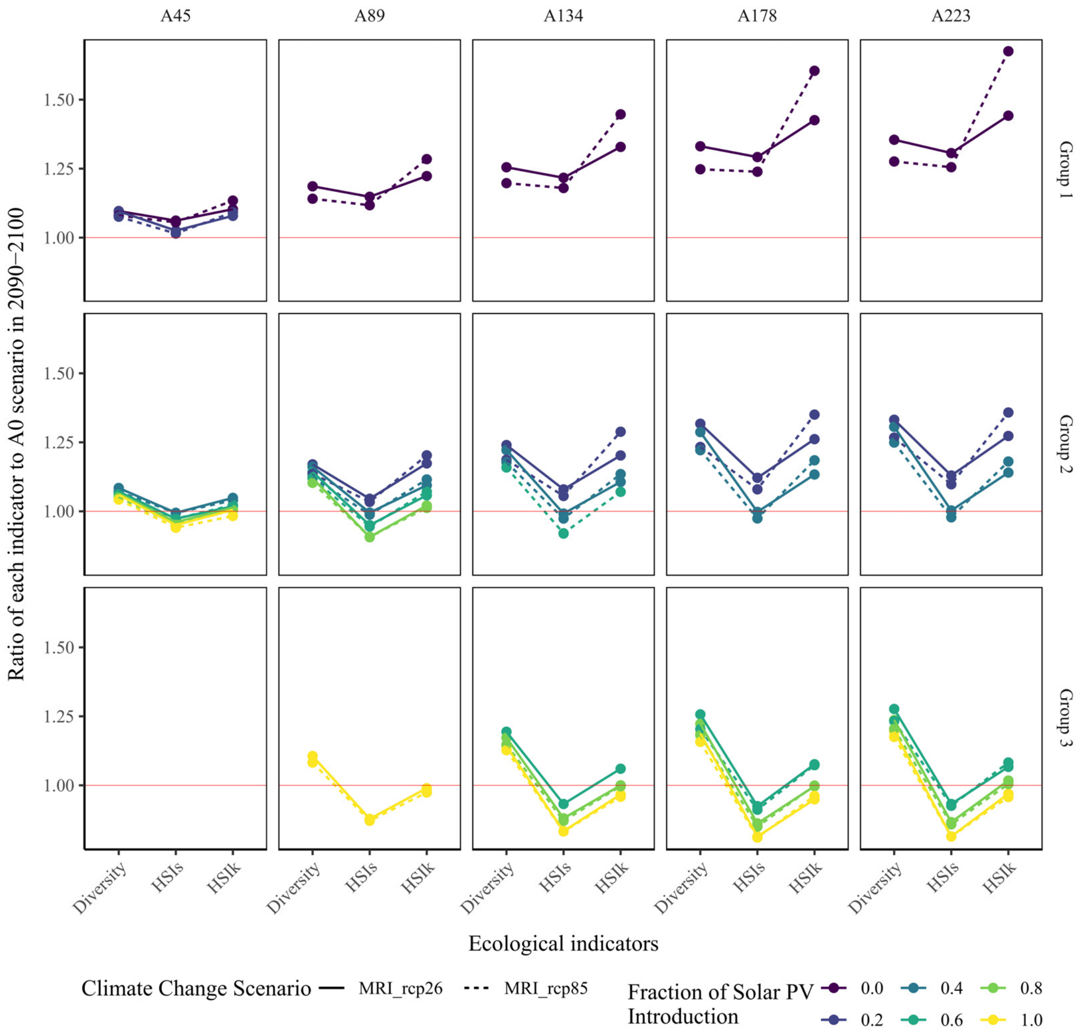

FIGURE 4 | Ratio of each ecological indicator to the no pastureland abandonment scenario (A0) from 2090 to 2100 by pastureland abandonment expansion speed and level of renewable energy production. The red line indicates the same indicator value as the A0 scenario. Values over 1.0 indicate that the ecological indicators are better than the A0 scenario. Three scenario groups were identified based on the balance between renewable energy (RE) supply and demand: group 1, where energy production is less than energy demand; group 2, where RE production satisfies the energy demand and is less than five times the demand; and group 3, where RE production satisfies the energy demand and is more than five times the RE demand. Diversity = Shannon–Wiener diversity index, HSI_s = habitat suitability index for the mountain hawk-eagle (*Spizaetus nipalensis orientalis*), HSI_k = habitat suitability index for Blakiston's fish owl (*Ketupa blakistoni blakistoni*). A0–A223 represents the pastureland abandonment expansion speed, and the colors indicate the solar PV plant fraction (**Table 1**).

2050 (United Nations, 2015; Predicting and Assessing Natural Capital and Ecosystem Services [PANCES], 2016; IPBES, 2020), our work implies that longer-term future vision and ecosystem management plans are required for pre-emptive actions.

Pastureland Abandonment–Renewable Energy–Raptorial Bird Habitat Nexus

Pastureland abandonment led to the expansion of mixed forests of broadleaf and conifer at landscape scales and, thus, increased the diversity and habitat suitability of the two raptorial birds (**Figure 3**). However, the decrease in the area of managed pastureland caused the loss of open areas and forest edge, which are used by the mountain hawk-eagle. For this reason, the HSI for the mountain hawk-eagle diminished or remained the same after 2030 (**Figure 3** and **Supplementary Figure 8**). In particular, the change of pastureland to solar PV plants reduced the open area and length of forest edge suitable for foraging environments (**Supplementary Figure 8**). As societies shrink, local managers need to select important pasturelands and maintain a mosaic of different ecosystems on them to conserve biodiversity hotspots.

Solar PV plants were located away from forests and more than 300 m from riversides to conserve the foraging environment of the mountain hawk-eagle and the nesting sites of the Blakiston's fish owl. Therefore, in scenarios with the small fractions of solar PV plants, the three ecological indicators were improved compared with the A0 scenario, which maintained the current land use (**Figure 4**). These indicators were improved because the contribution of transitional forests on abandoned pastureland exceeded the ecological impacts associated with solar PV installation at the landscape scale. Our results suggest that a better understanding of the nexus between pastureland abandonment, the introduction of multiple RE sources, and raptorial bird habitat would enable land managers to design local RE energy implementations to mitigate ecological impacts.

Renewable Energy–Biodiversity Nexus

By integrating the previous studies on RE mixes, spatially explicit ecological impact assessment, and process-based landscape modeling, this study has explored scenarios to meet both RE utilization and biodiversity conservation on an energy demand basis that is of interest to local stakeholders. Scenario 1 converted 80–100% of abandoned pastureland into biomass energy production, supplied 28–80% of the current regional energy demand, and improved the three ecosystem indicators. The residential population in the watershed is estimated to decrease to 4,118 by 2050 (48% of 2010) (National Land Numerical Information [NLNI], 2017). Considering that the energy demand will decrease from the current level as the population declines, group 1 could fulfill the regional energy demand, however, depending only on biomass energy would result in annual energy supply fluctuations (**Figure 3**). Therefore, mixing with other RE, as in the scenario of A45-S0.2, is recommended. In group 3, where the energy production far exceeded the current demand, more than 60% of abandoned pasture was converted to solar PV plant installation (**Figure 4**). The habitat suitability indices for the two raptorial birds, especially the mountain hawk-eagle, diminished compared with the A0 scenario, which maintained the current land use (**Figure 4**). In contrast, group 2, where the energy production and the current demand were almost of the same order, promotes the mixed use of solar PV plants and biomass energy. Group 2 produced more energy than the local demand and has the potential to supply energy to surrounding areas under a shrinking society. Concurrently, this mixed use of the two RE sources minimized the impact on the two habitat suitability indices (**Figure 4**). Therefore, both (1) combining multiple renewable energy sources and (2) arranging the spatial distribution of solar PV plant installations to avoid habitat degradation are essential for the production of sufficient energy while suppressing the impact on the ecosystem, as in groups 1 and 2. A participatory approach supported by scientific evidence can be effective in developing local future energy visions (Belmonte et al., 2015; Hori et al., 2019). Because our approach explicitly addresses not only ecological status but also energy supply potentials, it is useful for designing desirable future visions with different stakeholders to explore future visions that satisfy RE utilization and biodiversity conservation.

CONCLUSION AND FUTURE PERSPECTIVES

We identified nexuses between climate, vegetation, the habitat of the two raptorial bird species, and energy and successfully explored three future scenario groups: group 1 that improved plant species diversity and the habitat of the two raptorial bird species with less energy production than the current regional demand, group 2 that supplied sufficient energy production from the mixed use of woody biomass and solar PV systems while minimizing impacts on the three ecological indicators, and group 3 that resulted in high dependency on solar PV systems and the diminished habitat of the two raptorial bird species. Our quantitative modeling provides scientific information about energy–biodiversity nexuses for local stakeholder meetings, which contribute to developing land use and energy strategies.

To promote the use of quantitative forest landscape modeling to other areas, such as the Asia Pacific region, a reliable species parameter database is required for robust simulations. Our study suggests that the need for such a dataset is required, especially, for pioneer species. Currently, large accumulated datasets of traits (e.g., TRY, 2020) and occurrence maps of plant species (see, for example, GBIF, 2020; Tanaka and Matsui, 2007; Forestry Agency of Japan, 2019; Ministry of the Environment, Japan [MOE], 2020; Long Term Ecological Research [LTER], 2020) enable us to systematically prepare the standard parameters required for forest landscape simulation models. These standard datasets facilitate forest model intercomparison practice (Erickson and Strigul, 2019) and reduce uncertainties when simulating the vegetation dynamics of region-specific tree species under climate change.

Our results underestimate the effects of natural disturbance regimes, such as deer browsing and windthrow. In Japan, *Sasa* species play a key role in regeneration dynamics by preventing the establishment of other plant species. Because the vegetation map and forest registers used in this study lack detailed spatial distribution information of *Sasa* species, it is necessary to estimate its initial density from the overstory tree density (Tatsumi and Owari, 2013). Climate change and deer browsing affect the survival of *Sasa* species (Yokoyama and Shibata, 1998; Tsuyama et al., 2011, 2012). More frequent windthrow events and post-windthrow management under future climate will affect species composition and carbon dynamics (Lucash et al., 2019; Morimoto et al., 2019; Hotta et al., 2020). Therefore, integrative modeling of the nexus between (1) natural disturbances at a broader scale, (2) the distribution of *Sasa* species, and (3) regeneration dynamics under future climate change is a fundamental future perspective.

Recently, SSPs scenarios (O'Neill et al., 2014) have been developed in the climate change domain, and research is progressing to downscale global-scale scenarios to national scales (Frame et al., 2018; Guo et al., 2019; Chen et al., 2020). IPBES is also developing a Nature Futures Framework as a unified future scenario from the aspect of biodiversity conservation (PBL, 2018; IPBES, 2020). Local scenario analysis is thus expected to couple seamlessly with socio-economic conditions provided by such external scenarios. Through the modeling of the nexus between SDG goals 13 (Climate action) and 15 (Life on land), to which forest landscape modeling can contribute, nexus structures are expected to be identified for people, the planet, prosperity, peace, and partnership in collaboration with other research fields.

DATA AVAILABILITY STATEMENT

Input data and analysis scripts have deposited in our GitHub repository: https://github.com/hagachi/Project-RE-biodiversity-nexus-2020. The species parameters and calibration procedure can be found in the **Supplementary Material**. Redistribution of the forest registers, which were used for initializing landscapes, are restricted by the Forest Management Bureau of Hokkaido Prefecture. Requests to access the datasets should be directed to the bureau: https://www.rinya.maff.go.jp/hokkaido/keikaku/map/map.html (in Japanese).

AUTHOR CONTRIBUTIONS

CH, MM, TMt, and TMc contributed the conception, design, and analysis. WH, TI, and JM organized the vegetation and environmental dataset. CH, TI, and HS contributed the localization of forest landscape model. MN arranged the field survey. SH and OS provided the ideas and discussion for the design scenarios. CH and MM wrote the first draft of the manuscript. All authors contributed to the revision of the manuscript. CH and TMt finalized the submitted manuscript with input from all the authors.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fevo.2020.00155/full#supplementary-material

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