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ORIGINAL ARTICLE

Understanding Japan's Land-use Dynamics between 1987 and 2050 using Land Accounting and Scenario Analysis

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Abstract

Amidst global concerns about land use change and its far-reaching impact on biodiversity and human well-being, there is a growing need to understand how land use stock and flow changes over time through land use accounting. While existing studies on land accounting have focused on historical land changes, little attention has been paid to future transitions. This study assessed historical patterns and projected future shifts in land use dynamics from 1987 to 2050 across Japan by combining high-resolution land use and land cover datasets, land change simulations, and land accounting. In the analyses, particular attention was paid to the historical and future trends of farmland abandonment by leveraging data at 100-m resolution built on national vegetation surveys. High-resolution analysis of farmland abandonment issue with national scale in Japan is a novelty. From 1987 to 1998, the land stock analysis results showed a pronounced marked increase in residential land (10.4%) and grassland (16.9%); the flow analysis results showed that urban residential sprawl expansion was mainly formed by secondary (32.6%) and plantation (21.1%) forest areas, coinciding with increasing population and economic growth. Projections from 2010 to 2050 indicate a marked increase in abandoned farmland (67.2% per decade), a trend influenced by rapid population decline and presumably agricultural policies, especially significant in regions such as Hokkaido and Kyushu. The findings of this study are crucial for shaping policy and decision-making, underlining the need for sustainable land management strategies that effectively balance urban growth, agricultural productivity, and environmental preservation in Japan.

Keywords Land use · Land accounts · Future projection · Abandoned farmland · Shrinking society

Introduction

Land resources are integral to the planet's health, providing a myriad of ecosystem services that support human well-being (Hernández-Blanco et al. 2022). However, human activities have driven the degradation of nature and these services (Foley et al. 2005; IPBES 2019). Hence, how human actions affect natural ecosystems and their services must be comprehensively assessed to facilitate sustainable development (Ma 2005; Taelman et al. 2016). In this context, land accounting, a tool for monitoring systematic transitions in landscapes over specific periods, has gained recognition as a critical method for understanding and managing environmental changes (Pontius et al. 2004; Benefoh et al. 2018; Parra-Paitan and Verburg 2022).

Land use driven by human activities affects natural resources and ecosystem outputs and services. The European Environment Agency (EEA) developed a land accounting framework applied to CORINE's 44 land cover classes between 1990 and 2000 (EEA 2006). These insights greatly

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contributed to the European Environmental State and Outlook 2005 report (Weber 2007). Land accounting goes beyond observation, as it offers an assessment index for the dynamics of different land use and land cover (LULC) classes. Land accounts can capture not only the stock, but also flow and exchange of land between land types (including consumption and formation) and the total amount of turnover in detail, which cannot be obtained with statistical information. This approach is essential for understanding the impacts of urban development and other socioeconomic activities, including agriculture and forestry (EEA 2006; UN 2014; Bariamis et al. 2018). Land accounting is an integral component of the System of Environmental and Economic Accounts (SEEA), a framework that integrates economic and environmental data to improve our understanding of the complex interrelationships of social–ecological systems (UN 2003; Smith 2007).

Most existing studies on land accounting focus on historical land use changes from the past to the present. Some studies quantify land resource footprints by measuring food and non-food production land (Bringezu et al. 2012; Kastner et al. 2014; Bruckner et al. 2015), whereas others linked physical land accounting to land price changes and economic development (Nishimwe et al. 2020; Wentland et al. 2020). Furthermore, beyond economic considerations, land accounting can help to inform national ecosystem assessments as it can elucidate how land use underpins the provisioning of ecosystem services (Smith et al. 2000; Weber 2007; Ivanov and Eigenraam 2017; Kertész et al. 2019). Several regions and nations practice land accounting (Kumar 2011; Bariamis et al. 2018; Nishimwe et al. 2020). However, less attention has been paid to long-term change, a key aspect of environmental and sustainability planning in land use change accounting.

One of the major challenges in using land accounting to predict future land use patterns, especially in countries anticipating severe population decline, is the recognition and addressing of abandoned farmlands. Farmland abandonment is a global phenomenon, especially in developed countries (Keenleyside and Tucker 2010; Subedi et al. 2022), which substantially impacts biodiversity and the provision of ecosystem services (MacDonald et al. 2000; Queiroz et al. 2014; Li and Li 2017; Zanden et al. 2017; Ustaoglu and Collier 2018). In Japan, for instance, increased land abandonment has been identified as a major driver of biodiversity decline since 2007, as highlighted in the third edition of the National Biodiversity Strategies and Action Plan published by the Government of Japan (Ministry of the Environment 2007). Farmland abandonment affects food security and economic development (Liu and Zhou 2021; Liu et al. 2021) and causes substantial environmental damage (Foley et al. 2005; Bala et al. 2007). Moreover, agricultural abandonment has been described as a factor in biodiversity decline in many high-income nations (Lindborg and Eriksson 2004; Báldi and Batáry 2011; Queiroz et al. 2014; Uchida and Ushimaru 2014). Agricultural landscapes contain semi-natural habitats, such as grassland, wetlands, and secondary forests that provide important habitats for a plethora of plant and animal species (Huang et al. 2020). Farmland abandonment can lead to the neglect and loss of these semi-natural habitats as they become underused or are converted into other land use types, intensifying the damage caused by wild animals. Such habitat loss and damage can result in declines in biodiversity. In Japan, underuse is one of the four biodiversity crises (Ministry of the Environment 2021; UNU 2010). Several countries in Europe, East Asia, and Oceania have reported underuse crises (Mauerhofer et al. 2018). In Japan, depopulation, especially in rural areas, is a major driver, and its connection with land use change tendencies toward abandoned farmland is currently under investigation (Yoshihara 2017; Kobayashi et al. 2020; Mameno and Kubo 2022; Imai et al. 2023). Given the ongoing social and biophysical changes in Japan, assessing current and future land use dynamics is crucial for mitigating the extent of farmland abandonment and its environmental consequences.

Abandoned farmland poses a unique challenge in land use change analysis because it is often not distinctly recognized as an independent land use class in existing datasets, thus complicating efforts to accurately assess its future expansion. Land accounting is a general method of quantifying land resources. The specific point here is the utilization of the abandoned farmland category in national vegetation surveys, as it has not yet been considered at a national-level 100-m resolution to project future land use. Shoyama et al. (2021) conducted a detailed scenario analysis of future land use patterns in Japan with a 500-m resolution by introducing an additional land use class specifically for abandoned farmland. However, this approach resulted in a severe underrepresentation of abandoned farmland areas, capturing only 0.3% of the total abandoned farmland under the business as usual (BaU) scenario (Shoyama 2021). This discrepancy is largely attributable to small-scale farming in Japan. The average farmland area owned per farm household is approximately 0.01 km^2 (MAFF 2010). A 500-m resolution was still too coarse to effectively capture the spatial distribution of abandoned farmland. Kobayashi et al. (2020) suggested that further improvements in the spatial resolution of land use datasets are essential to capture and represent abandoned farmland (Kobayashi et al. 2020). In Japan, abandoned farmland prediction was conducted using socioeconomic factors to conduct future projections, but in this study, we mainly used spatial factors (Matsui et al. 2014).

In this study, we examine Japan's land use dynamics, spanning historical patterns to future projections for the periods of 1987–1998 and 2010–2050, offering crucial insights for informed policymaking and sustainable land management strategies in Japan and beyond. Using future projection results to conduct land accounting contributes to a concrete image for land use management. We expect that this study will help in proposing sustainable land use management toward 2050 at the local and national levels. To achieve this, we initially created a land use dataset with a 100-m resolution for 1987 and 1998 using national vegetation survey data. By employing a more refined land use dataset, we attempted to overcome the constraints of previous methodologies, wherein abandoned farmland was underrepresented. This spatial high-resolution study is especially important for discussing farmland abandonment in Japan. Land abandonment is not an issue unique to Japan; it is attracting attention internationally. We expect this study can contribute to future modeling in farmland abandonment research.

Material and methods

Land use and land cover materials

We first created an LULC dataset, which formed the basis for future land use projections and accounting, and was developed following Shoyama's methodology using historical data from National Vegetation Surveys conducted by the Ministry of the Environment of Japan (Shoyama et al. 2019; Shoyama 2021). These vegetation surveys are conducted at 5-year intervals and the maps categorize vegetation into 905 distinct classes across Japan, with abandoned farmland as a separate category. The reason for using National Vegetation Surveys for analysis is that they are the only land use data from official surveys in Japan with an independent category for abandoned farmland. We downloaded the land use data from the Biodiversity Center of Japan, Environment Ministry of Japan. Three types of land use data were uploaded to the GIS database: the second and third vegetation map from a survey conducted from 1978 to 1987 (named as LU1987), the fourth and fifth vegetation map from a survey conducted from 1988 to 1998 (named as LU1998), and the sixth and seventh vegetation map, using data for which collection commenced in 1999 and is continuing (named as LU2014). The data used in this study were generalized into ten broad categories by Biodiversity Division, NIES Japan (https://www.nies.go.jp/biology/data/lu.html) (Ogawa et al. 2020; Shoyama 2021). At this time point, the integrity of LU2014 was approximately 80%. Consequently, we used maps LU1987 and LU1998 as a basis for projecting future land use and used the incomplete LU2014 only for model validation.

To improve the accuracy of land accounts and future land change simulations, we rasterized the vector-based map to a grid resolution of 100 × 100 m. This level of detail is the highest resolution achieved for a national-scale land account study in Japan. The ten broad categories included residential land (RES), paddy fields (PAD), croplands (CRP), other agricultural land (OAL), abandoned farmland (ABF), grassland (GRS), natural forest (NFR), secondary forest (SFR), plantation forest (PFR), and other land uses (OLU). The specific definitions of each category are listed in Supplementary Table S1. These ten categories are used for land accounting and land use projection purposes.

Land use projection methods

To project LULC for 2050, we employed the Land Change Modeler (LCM) tool in TerrSet 18.3 software. The LCM generates future land use maps using complex multi-objective allocation algorithms. These algorithms combine projections of future land demand with location-specific data derived from transition potential modeling (Eastman et al. 2016). The process of land use projection within the LCM framework covers several key steps, including the analysis of past land use changes, transition potential modeling, land-demand setting, future land use projection, and validation (Fig. 1).

LCM simulation procedures

The initial step of the LCM analysis was to model past land use changes using LU1987 and LU1998 data, both at 100-m grid resolution at a national scale. We evaluated land changes for this period to assess transitions quantitatively and spatially across different land use classes. By modeling these transitions, known as transition potentials, we projected future land use by incorporating user-specified drivers of change (Mishra and Rai 2016). According to the TerrSet manual (Eastman et al. 2016), we used a multilayer perceptron (MLP) neural network to consider all drivers in this model. The MLP neural network can also model relationships between non-linear variables. This network is based on the supervised backpropagation training algorithm and consists of at least three layers of nodes, including an input layer, output layer, and array of hidden layers that represent relationships between independent and dependent variables (Atkinson and Tatnall 1997). We considered 23 independent variables (Table 1), classified into anthropogenic and natural drivers (Mitsuda and Ito 2011; Hashimoto et al. 2018; Huang et al. 2021). Within these categories, anthropogenic drivers included variables such as transportation and surrounding land use, whereas natural drivers included elevation and slope. The land use simulation process involved generating transition potentials that were visually represented as maps to illustrate the potential for land change at specific times, which are crucial for predicting future land use (Kamaraj and Rangarajan 2022). Each transition potential within the simulation sub-models corresponded to a single land transition.

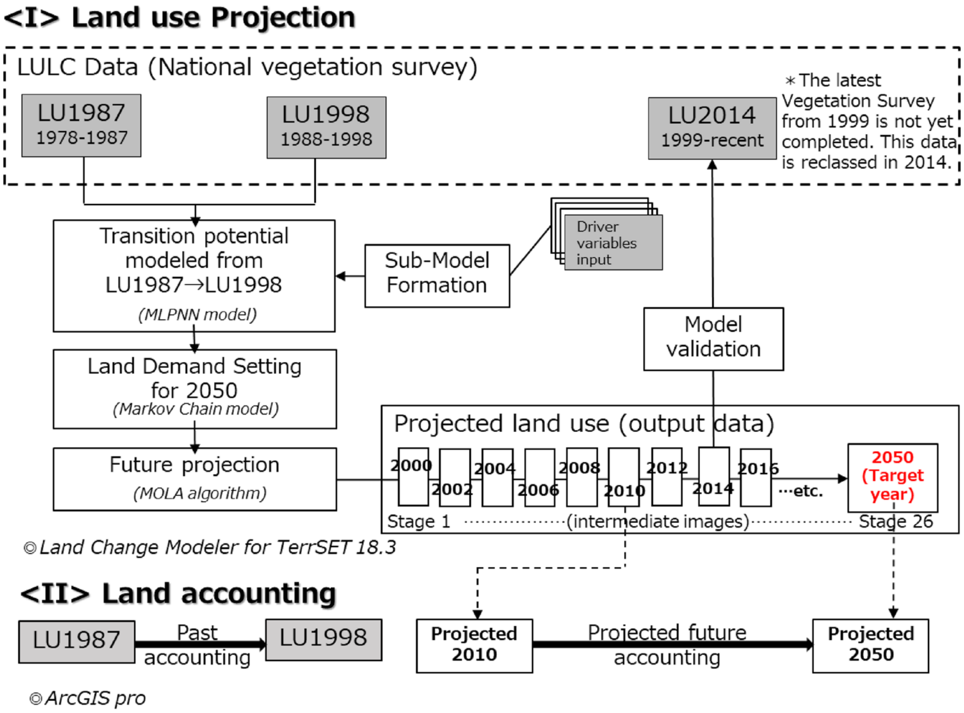


Fig. 1 The process of future land projection by Land Change Modeler and land use transition by ArcGIS pro

Table 1 Independent variables for land use simulation Source: NLNI (National Land Numerical Information); ESRI JAPAN (https://www.esrij.com/products/data-content-geosuite-chikei/)

Variables	Description	Structure	Normalization	Static/dynamic	Time	Source
X1	Past land use change between LU1987 and LU1998	Categorical	Evidence likelihood	Static	1987, 1998	NLNI
X2	Distance to abandoned farmland (m)	Continuous	Natural log	Dynamic	1987	NLNI
X3	Distance to grassland (m)	Continuous	Natural log	Dynamic	1987	NLNI
X4	Distance to cropland (m)	Continuous	Natural log	Dynamic	1987	NLNI
X5	Distance to natural forest (m)	Continuous	Natural log	Dynamic	1987	NLNI
X6	Distance to other agricultural land (m)	Continuous	Natural log	Dynamic	1987	NLNI
X7	Distance to other land use (m)	Continuous	Natural log	Dynamic	1987	NLNI
X8	Distance to paddy (m)	Continuous	Natural log	Dynamic	1987	NLNI
X9	Distance to plantation forest (m)	Continuous	Natural log	Dynamic	1987	NLNI
X10	Distance to residential land (m)	Continuous	Natural log	Dynamic	1987	NLNI
X11	Distance to secondary forest (m)	Continuous	Natural log	Dynamic	1987	NLNI
X12	Density of abandoned farmland (dimensionless)	Continuous	–	Static	1987	NLNI
X13	Density of grassland (dimensionless)	Continuous	–	Static	1987	NLNI
X14	Density of cropland (dimensionless)	Continuous	–	Static	1987	NLNI
X15	Density of natural forest (dimensionless)	Continuous	–	Static	1987	NLNI
X16	Density of other agricultural land(dimensionless)	Continuous	–	Static	1987	NLNI
X17	Density of other land use (dimensionless)	Continuous	–	Static	1987	NLNI
X18	Density of paddy (dimensionless)	Continuous	–	Static	1987	NLNI
X19	Density of plantation forest (dimensionless)	Continuous	–	Static	1987	NLNI
X20	Density of residential land (dimensionless)	Continuous	–	Static	1987	NLNI
X21	Density of secondary forest (dimensionless)	Continuous	–	Static	1987	NLNI
X22	Elevation (m)	Continuous	–	Static	2020	ESRI JAPAN
X23	Slope (°)	Continuous	–	Static	2020	ESRI JAPAN

Distance variables represent the natural Euclidean log transformation from a given land use category; density variables represent the land use density of a given land use category with a 100-m-radius neighborhood

The accuracy of these transitions was measured based on the transition skill measure, which served as a reference for determining the transitions to be included in the projection model (Gibson et al. 2018). To calculate land demand, we used the Markov chain method, which creates a transition matrix for projection (Burnham 1973). Future land use for 2050 was then projected using a multi-objective land allocation algorithm, incorporating these transition potentials and land demand (Eastman et al. 1995).

However, considering Japan's ongoing depopulation trend, future land demand projections, especially for residential land, might be overestimated if based solely on past trends (Hashimoto et al. 2018; Huang et al. 2021). Therefore, rather than using the standard land transition potential matrix produced by the LCM, we adjusted the matrix to align it with the government-driven forecasting data for 2050 (described below). This approach aims to reflect land use more accurately under BaU scenarios. Details of these steps are explained in the following sections. To project future land use with LCM, the number of dynamic variable recalculation stages must be set. We set the stage to 26 and used the intermediate image of stage 8 to validate our model accuracy using the LU2014 vegetation survey results (Fig. 1). We calculated the operating characteristic curve (ROC) statistic for model validation. Owing to the high computational power and memory requirements for performing this analysis at 100-m resolution for all of Japan, we divided the country into four blocks (A to D) for the LCM simulation (Fig. 2). After running the LCM on each block, the projection results were merged to form a comprehensive national land-accounting map. The division of Japan into four blocks was a strategic choice, considering the country's extensive length of 3000 km from north to south.

Estimating land demand for 2050

To estimate the land demand for 2050, we considered Japan's population trends and social background. The national population peaked at 128 million in 2008 and is projected to decline to 97 million by 2050 (National Institute of Population and Social Security Research 2017). Based on this projection and referring to other future projection studies (Shoyama et al. 2019; Shoyama 2021), we assumed that the demand for residential land in 2050 would remain at the same level as that observed in the LU1998 dataset under a BaU trend.

Depopulation has considerably affected agricultural land use, leading to increased abandonment. Statistics from the Ministry of Agriculture, Forestry, and Fisheries indicate that agricultural land decreased by 2.4% from 2008 to 2014, with two-thirds of this reduction attributed to abandonment. Without the implementation of effective agricultural revitalization policies, abandoned farmland is expected to expand substantially after 2008 (MAFF 2016). We projected that, by 2050, agricultural land would account for 15.0% (56,248 km^2) of total land use, with abandoned farmland accounting for 3.6% (13,482 km^2). This projection includes paddy fields, cropland, and other agricultural farmland, and their respective proportions were derived from recent statistical reports. Comparisons between the amount of abandoned farmland in the vegetation maps and administrative statistics (MAFF 2016) revealed discrepancies; for instance, the proportion of abandoned farmland was around 6% in 1998, but only approximately 0.8% in the satellite-based vegetation maps. This disparity arose from the different definitions and inconsistent measurements of farmland abandonment, as lands registered for agricultural use may be misclassified as forests or grassland in vegetation maps if they are overgrown (Zanden et al. 2017). Consequently, we reconciled these differences in land demand settings.

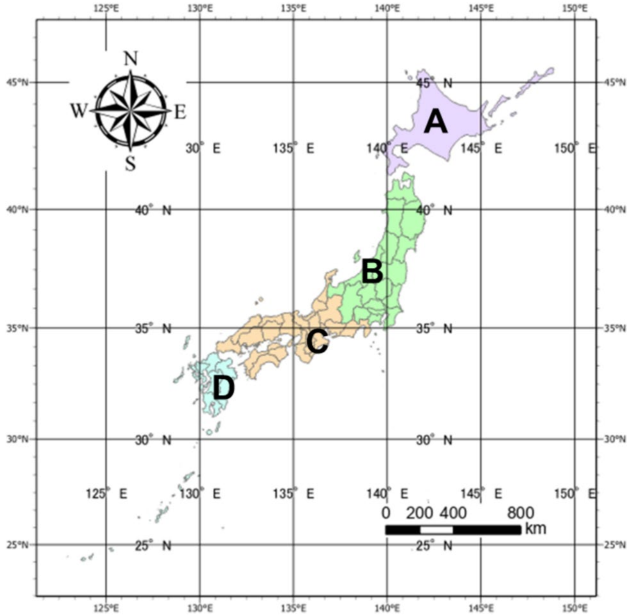


Fig. 2 Japan national land was separated to four blocks in the Land Change Modeler simulation procedure

For grassland and other land use types, we assumed that the proportions would remain consistent with the LU1998 levels. Although grassland increased substantially between LU1987 and LU1998, it was not included as a factor in projecting future land use because of the anticipated natural reforestation in the cut-over forest areas. However, natural forest plant succession may be hindered by factors such as the proliferation of the Japanese Sika deer (*Cervus nippon*), which experienced explosive growth in the 1990s (Takatsuki 2009). The Japanese Sika deer (*C. nippon*) can hinder plant regeneration by consuming seedlings and stripping bark, impacting natural reforestation (Akashi and Nakashizuka 1999; Nagaike 2020). Thus, it would be inappropriate to assume a straightforward conversion from grassland to forests by 2050. After determining land demand for residential, agricultural, grassland, and other uses, forest land (comprising natural, secondary, and plantation forests) was allocated to balance the remaining land demand.

Model validation

The number of transitions varied across the four designated blocks: block A consisted of 28 transitions, blocks B and C each had 27 transitions, and block D consisted of 29 transitions. The transitions common to all blocks are shaded in gray in Table 2.

Generally, for sub-models with low accuracy, it is recommended to omit such transitions from model development because they might skew the results. However, some sub-models with relatively low accuracy were included to enhance the flexibility of our later scenario analysis. For example, the transitions from secondary forest to abandoned farmland and cropland to plantation forest in block A exhibited the lowest accuracy and transition skill measures. However, excluding these transitions could result in their absence from future projections, which is undesirable. The primary goal of our modeling was to obtain a BaU land projection for 2050, including a range of other potential transitions that were considered essential for accommodating different future scenario projections. ROC statistics were used to validate the results (Parsamehr et al. 2020).

The projection maps were used to calculate the ROC statistics, with the AUC values indicating the accuracy of the model (Olmedo et al. 2022). As shown in Table 2, the AUC values of each block were notably high: 0.92, 0.81, 0.86, and 0.99 for blocks A, B, C, and D, respectively. These high values indicate that the land use transition models are sufficiently robust to project future land use patterns by 2050.

Land accounting method

Land stock accounting

The accounting of land stock involves several key indicators, such as loss and gain, net change, and turnover area over a specified period (EEA 2006; Nishimwe et al. 2020). These indicators are crucial for quantifying changes in land use and exploring their characteristics and implications (Weber 2007; Hashimoto et al. 2018; Shoyama et al. 2019). In this context, loss and gain refer to the flows of formation and consumption for each land category, respectively. The net change and turnover indicators were estimated by subtracting and summating the loss and gain values, respectively. The net change indicator represents the total land area at the end of the period, whereas turnover helps in understanding the amount of initial stock carried over to the end of that period. The turnover proportion is an important indicator of sustainable development. Our land stock account analysis covered two periods: historical land use change from LU1987 to LU1998 and projected land use change from 2010 to 2050. The time spans differed between LU1978–LU1998 and 2010–2050, so we analyzed and observed the change tendencies in this study. When selecting the 2010–2050 period, we considered biodiversity and sustainability. The Basic Act on Biodiversity established in 2008 was the first law in Japan to preserve biodiversity. It stipulates the responsibilities of not only the national government, but also local governments and private organizations, to make efforts to formulate and implement the conservation and sustainable use of biodiversity. We chose 2010 as the starting year for discussing the future land use change tendency because 2010 was more practical for data collection in multiple statistics.

Land flow accounting

Land flow accounting is a framework designed to robustly and systematically analyze land-related changes, facilitating the identification of crucial patterns and trends that can serve as a basis for SEEA (Weber 2007; Feranec et al. 2010). In Europe, the CORINE Land Cover (CLC) processed by the EEA provides comparable information on LULC changes at the continental scale (Kolar 2001). This study used these methods to record changes in LULC (Table 3).

The land change flow (LCF) account has been effective in describing land use changes and estimating potential impacts on ecosystems (Poschlod et al. 2005; Haines-Young 2009). The LCFs in the EEA encompassed nine patterns; however, our study only used six (Supplemental Material, Table S2). These include LCF2 for "urban residential sprawl," LCF4 for "agricultural internal conversions," LCF5 for "conversion from forested and natural land to agriculture," LCF6 for "withdrawal of farming," LCF7 for "forest creation and management," and LCF9 for "change due to natural and multiple causes." This classification aids in assessing the land cover consumed or formed over a specific period and categorizing the reasons for land use changes (e.g., urban sprawl or agricultural land loss).

As previously stated, in this study, land account calculations were performed at a 100-m resolution, allowing for detailed observations of spatial differences. However, the high resolution poses the risk of identifying specific locations, potentially leading to privacy and security policy breaches. Therefore, instead of directly displaying results in a 100-m grid map, we used the Jenks optimization method to estimate the areas of each LCF indicator and present the distribution of 1747 municipalities across Japan, the smallest unit of local government in Japan. This analysis is valuable for administrative guidance and policy implementation.

Table 2 Transition potential selection and model accuracy (AUC) of the models for the four blocks

Block A				Block B				Block C				Block D			
No	Sub-model	Accuracy	Transition skill measure	No	Sub-model	Accuracy	Transition skill measure	No	Sub-model	Accuracy	Transition skill measure	No	Sub-model	Accuracy	Transition skill measure
1	**RES to OAL**	96.23	0.93	1	**OLU to PFR**	93.55	0.87	1	**RES to CRP**	92.00	0.84	1	**RES to SFR**	100.00	1.00
2	**RES to SFR**	88.89	0.78	2	GRS to SFR	91.00	0.82	2	**RES to OAL**	91.44	0.83	2	**RES to PFR**	100.00	1.00
3	**RES to GRS**	88.24	0.76	3	CRP to PFR	89.89	0.80	3	**RES to SFR**	90.12	0.80	3	RES to PAD	100.00	1.00
4	ABF to GRS	87.85	0.76	4	GRS to PFR	87.68	0.75	4	**RES to PFR**	88.89	0.78	4	**RES to CRP**	91.30	0.83
5	**RES to CRP**	86.49	0.73	5	**PAD to ABF**	86.05	0.72	5	**RES to GRS**	86.08	0.72	5	ABF to CRP	85.71	0.71
6	NFR to CRP	83.93	0.68	6	PAD to PFR	83.43	0.67	6	**OLU to RES**	83.67	0.67	6	**OLU to RES**	82.20	0.64
7	ABF to OAL	81.05	0.62	7	**RES to SFR**	82.84	0.66	7	**PAD to ABF**	82.76	0.66	7	PFR to SFR	77.20	0.54
8	ABF to OLU	78.39	0.57	8	**RES to OAL**	82.74	0.65	8	RES to PAD	80.00	0.60	8	RES to OLU	75.23	0.50
9	ABF to CRP	77.73	0.55	9	**RES to GRS**	81.71	0.63	9	PAD to SFR	79.49	0.59	9	SFR to OAL	74.24	0.48
10	**OLU to RES**	76.58	0.53	10	**GRS to RES**	80.67	0.61	10	CRP to SFR	79.17	0.58	10	**SFR to PFR**	70.42	0.41
11	CRP to RES	76.16	0.52	11	NFR to PFR	80.36	0.61	11	PAD to PFR	77.62	0.55	11	**GRS to RES**	69.14	0.38
12	NFR to OLU	76.10	0.52	12	**SFR to PFR**	79.85	0.60	12	**GRS to RES**	74.08	0.48	12	**SFR to RES**	68.54	0.37
13	CRP to ABF	76.03	0.52	13	OAL to PFR	79.50	0.59	13	OAL to SFR	73.64	0.47	13	NFR to GRS	68.45	0.37
14	**GRS to RES**	75.60	0.51	14	**RES to PFR**	77.65	0.55	14	SFR to OLU	72.27	0.45	14	**PAD to ABF**	68.34	0.37
15	**PAD to ABF**	74.54	0.49	15	NFR to RES	76.04	0.52	15	PAD to CRP	72.19	0.44	15	OAL to ABF	66.99	0.34
16	OAL to RES	71.74	0.43	16	**RES to CRP**	75.29	0.51	16	**SFR to RES**	70.25	0.41	16	ABF to OAL	66.67	0.33
17	**SFR to RES**	70.94	0.42	17	RES to PAD	73.29	0.47	17	NFR to RES	68.85	0.38	17	**SFR to GRS**	66.55	0.33
18	**ABF to RES**	67.81	0.36	18	**SFR to RES**	70.14	0.40	18	**PFR to RES**	68.42	0.37	18	CRP to ABF	65.44	0.31
19	NFR to PFR	66.60	0.33	19	**PFR to RES**	68.82	0.38	19	NFR to GRS	67.76	0.36	19	NFR to RES	65.23	0.30
20	NFR to RES	65.35	0.31	20	NFR to GRS	67.25	0.35	20	CRP to RES	66.68	0.33	20	**PAD to RES**	62.47	0.25
21	OAL to ABF	64.65	0.29	21	**ABF to RES**	63.61	27.22	21	OAL to RES	64.19	0.28	21	PFR to GRS	62.28	0.25
22	**PAD to RES**	63.41	0.27	22	**PAD to RES**	63.45	0.27	22	**SFR to PFR**	63.45	0.27	22	**PFR to RES**	61.68	0.23
23	**PFR to RES**	62.13	0.24	23	**SFR to GRS**	63.32	0.27	23	PFR to GRS	61.70	0.23	23	OAL to GRS	61.43	0.23
24	**SFR to PFR**	61.35	0.23	24	ABF to OAL	60.43	0.21	24	**SFR to GRS**	61.38	0.23	24	CRP to RES	60.48	0.21
25	**SFR to GRS**	60.42	0.21	25	CRP to RES	60.20	0.20	25	ABF to SFR	58.30	0.92	25	OAL to RES	60.07	0.20
26	**RES to PFR**	60.00	0.20	26	PFR to GRS	60.11	2.22	26	**ABF to RES**	57.62	0.15	26	**RES to GRS**	59.09	0.18
27	SFR to ABF	52.63	0.05	27	OAL to RES	59.57	0.19	27	**PAD to RES**	50.18	0.00	27	**RES to OAL**	56.00	0.12
28	CRP to PFR	51.72	0.03									28	**ABF to RES**	52.78	0.06
												29	OAL to OLU	51.02	0.02
	Model AUC=		0.92		Model AUC=		0.81		Model AUC=		0.86		Model AUC=		0.99

Transitions with bold shadow shared the same transition within the four models

Table 3 Classification of land use transition for the periods of LU1987–LU1998 and projected 2010–2050

Previous land use	Later land use									
	RES	PAD	CRP	OAL	ABF	GRS	NFR	SFR	PFR	OLU
RES	NC	LCF5	LCF5	LCF5	LCF5	LCF7	LCF7	LCF7	LCF7	LCF9
PAD	LCF2	NC	LCF4	LCF4	LCF6	LCF6	LCF6	LCF6	LCF6	LCF9
CRP	LCF2	LCF4	NC	LCF4	LCF6	LCF6	LCF6	LCF6	LCF6	LCF9
OAL	LCF2	LCF4	LCF4	NC	LCF6	LCF6	LCF6	LCF6	LCF6	LCF9
ABF	LCF2	LCF5	LCF5	LCF5	NC	LCF6	LCF6	LCF6	LCF6	LCF9
GRS	LCF2	LCF5	LCF5	LCF5	LCF5	NC	LCF7	LCF7	LCF7	LCF9
NFR	LCF2	LCF5	LCF5	LCF5	LCF5	LCF7	NC	LCF7	LCF7	LCF9
SFR	LCF2	LCF5	LCF5	LCF5	LCF5	LCF7	LCF7	NC	LCF7	LCF9
PFR	LCF2	LCF5	LCF5	LCF5	LCF5	LCF7	LCF7	LCF7	NC	LCF9
OLU	LCF2	LCF5	LCF5	LCF5	LCF5	LCF9	LCF7	LCF7	LCF7	NC

LCF2 → urban residential sprawl, LCF4 → agriculture internal conversions, LCF5 → conversion from forested and natural land to agriculture, LCF6 → withdrawal of farming, LCF7 → forest creation and management, LCF9 → change due to natural and multiple causes (source: European Environment Agency, 2006. Land Accounts for Europe 1990–2000: Towards Integrated Land and Ecosystem Accounting)

RES residential land, *PAD* paddy field, *CRP* cropland, *OAL* other agricultural land, *ABF* abandoned farmland: *GRS* grassland, *NFR* natural forest, *SFR* secondary forest, *PFR* plantation forest, *OLU* other land use, *NC* no change

Results

Accounting of land stock and flow changes from LU1987 to LU1998

Table 4 displays the changes in land stock between LU1987 and LU1998, detailing the losses and gains across various land-cover classes. During this period, the highest loss was observed in secondary forest (39.6%), followed by plantation (22.1%) and natural forest (17.8%). Grassland (33.6%), residential land (23.3%), and plantation forest (20.7%) accounted for the majority. The net change value, which represents the net formation of land cover, shows the extent of change in absolute terms and as a percentage

Table 4 Land stock account for LU1987–LU1998 and projected 2010–2050

	RES	PAD	CRP	OAL	ABF	GRS	NFR	SFR	PFR	OLU
LU1987–LU1998										
LU1987 (a) (km^2)	21,989	42,386	19,837	14,673	682	15,931	64,559	91,274	93,476	9527
Loss (km^2)	70	494	301	183	38	721	1807	4012	2239	264
Loss/sum of loss (%)	0.7%	4.9%	3.0%	1.8%	0.4%	7.1%	17.8%	39.6%	22.1%	2.6%
Gain (km^2)	2356	47	552	306	8	3407	61	364	2092	936
Gain/sum of gain (%)	23.3%	0.5%	5.5%	3.0%	0.1%	33.6%	0.6%	3.6%	20.7%	9.2%
Net-change (gain − loss)/a (%)	10.4%	− 1.1%	1.3%	0.8%	− 4.4%	16.9%	− 2.7%	− 4.0%	− 0.2%	7.0%
Turnover (gain + loss)/a (%)	11.0%	1.3%	4.3%	3.3%	6.6%	25.9%	2.9%	4.8%	4.6%	12.6%
LU1998 (b) (km^2)	24,274	41,938	20,088	14,796	652	18,617	62,814	87,626	93,329	10,198
Projected 2010–2050										
Projected 2010 (a) (km^2)	24,214	39,584	18,585	13,861	3655	18,572	62,726	88,029	94,623	10,071
Loss (km^2)	0	7775	4928	3224	0	0	0	865	617	0
Loss/sum of loss (%)	0.0%	2.1%	1.3%	0.9%	0.0%	0.0%	0.0%	0.2%	0.2%	0.0%
Gain (km^2)	0	0	0	156	9826	0	0	2390	5046	0
Gain/sum of gain (%)	0.0%	0.0%	0.0%	0.9%	56.4%	0.0%	0.0%	13.7%	29.0%	0.0%
Net change (gain − loss)/a (%)	0.0%	− 19.6%	− 26.6%	− 22.1%	268.8%	0.0%	0.0%	1.7%	4.7%	0.0%
Turnover (gain + loss)/b (%)	0.0%	19.6%	26.6%	24.4%	268.8%	0.0%	0.0%	3.7%	6.0%	0.0%
Projected 2050 (b) (km^2)	24,214	31,808	13,647	10,793	13,482	18,572	62,726	89,555	99,053	10,071

The time span of land stock is different between "LU1987–LU1998" and "Projected 2010–2050". By adjusting the amount of change to the same time span, the accounting results could be compared. For example, the net change of ABF is 268.8% for 40 years, but 67.2% for one decade of the initial stock in each category. Comparing the net change percentages of each category, grassland (16.9%) exhibited the largest increase, followed by residential land (10.4%), whereas the most notable decreases were observed in abandoned farmland (− 4.4%) and secondary forest. The turnover metric, which indicates the percentage of the initial stock that experienced change during the period, is a critical indicator of land accounting for sustainable land use (EEA 2006). Grassland displayed the highest turnover (25.9%), followed by other land use types (12.6%) and residential land (11.0%). Further analysis showed that over 40% of the grassland category comprised cut-over forests designated for natural restoration. Conversely, the other land use category predominantly included water bodies, exceeding 70% of its composition.

Table 5 shows the land flow from LU1987 to LU1998, illustrating the exchange of land cover between the different categories and their significance. Figure 3a displays these LCF indicators, revealing the geographical characteristics of land use change during this period. LCF2, LCF7, and LCF9 were particularly prominent. LCF2 contributed considerably (approximately 2356 km^2) to the residential land expansion, primarily originating from secondary (767 km^2) and plantation (491 km^2) forests. This trend of noticeable urban residential sprawl is evident around major cities, such as Tokyo and Osaka, which are population centers in Japan (Fig. 3a). LCF4 had a relatively minor impact (77 km^2) and was mainly concentrated in the Kanto region (Table 5; Fig. 3a). For LCF5, most of the land consumption occurred in secondary forests (261 km^2) and was predominantly converted to cropland (511 km^2) in the northern and central regions. LCF6, although showing minimal change, was concentrated in northern Tohoku, which largely comprises forests and grassland (Table 5). LCF7 indicated a major shift from secondary forest (2604 km^2) to grassland (3343 km^2) and plantation forest (2035 km^2), highlighting the widespread forest management practices during this period, especially in northern Tohoku (Fig. 3a). LCF9, which played a minor role in land use changes (954 km^2), involved transitions primarily from secondary forest and plantations to other land uses in LU1998, particularly in central Japan.

Accounting of projected land use changes and trends from 2010 to 2050

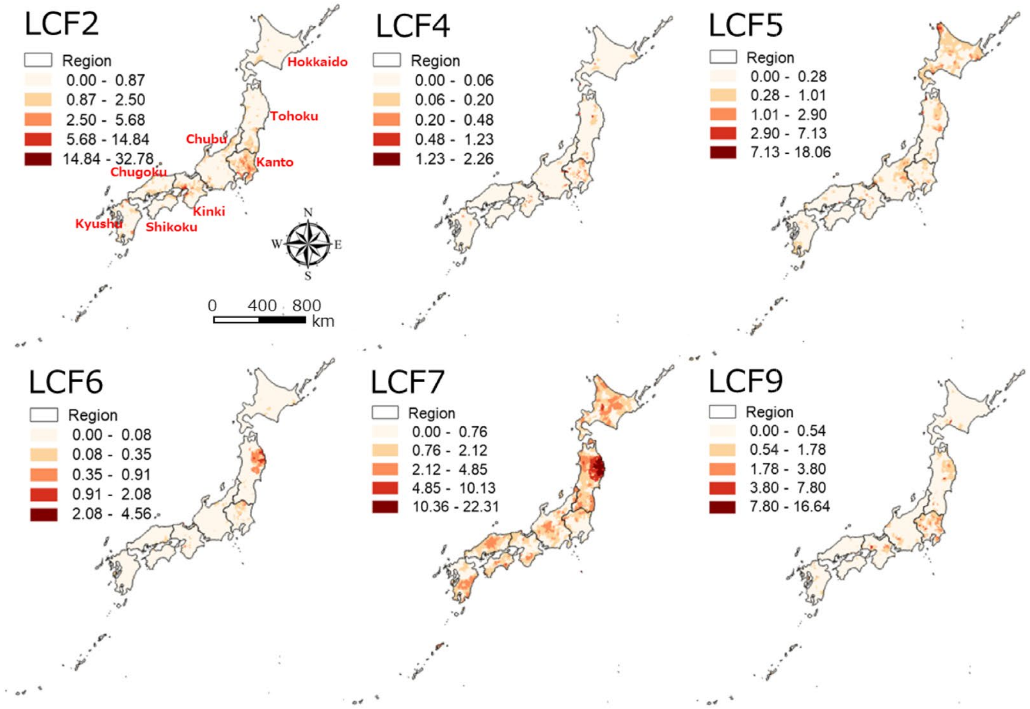
Table 4 provides the projected land stock changes from 2010 to 2050, simulated using the LCM. These projections indicate the influence of land demand on land stock during the simulation process. Notably, the simulation predicted an increase in abandoned farmland, whereas agricultural land (comprising paddy fields, cropland, and other agricultural land) was expected to experience the greatest loss.

Table 5 Land flow account describing the process of historical land cover changes from LU1987 (vegetation survey in 1978–1987) to LU1998 (vegetation survey in 1988–1998)

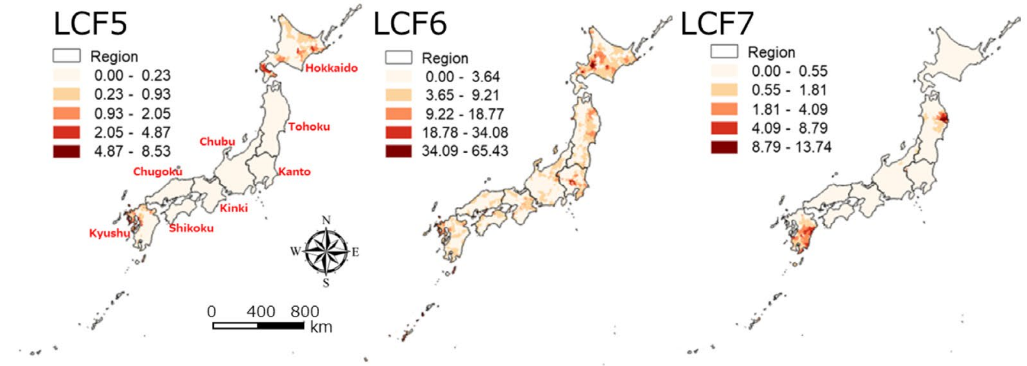
(Unit: km^2)	RES	PAD	CRP	OAL	ABF	GRS	NFR	SFR	PFR	OLU	Total
LCF2	0	376	149	108	21	127	156	767	491	160	2356
LCF4	0	30	22	25	0	0	0	0	0	0	77
LCF5	28	0	0	0	8	118	162	261	237	16	830
LCF6	0	43	92	28	3	0	0	0	0	0	166
LCF7	13	0	0	0	0	413	1407	2604	1238	70	5746
LCF9	29	45	38	22	6	64	82	380	272	18	954
Total consumption of 1987 land cover	70	494	301	183	38	721	1807	4012	2239	264	10,128
No change	21,919	41,892	19,536	14,490	645	15,210	62,752	87,262	91,237	9263	364,205
Total land cover 1987	21,989	42,386	19,837	14,673	682	15,931	64,559	91,274	93,476	9527	374,333
LCF2	2356	0	0	0	0	0	0	0	0	0	2356
LCF4	0	8	41	28	0	0	0	0	0	0	77
LCF5	0	39	511	277	3	0	0	0	0	0	830
LCF6	0	0	0	0	5	46	2	56	57	0	166
LCF7	0	0	0	0	0	3343	59	308	2035	0	5746
LCF9	0	0	0	0	0	18	0	0	0	936	954
Total formation of 1998 land cover	2356	47	552	306	8	3407	61	364	2092	936	10,128
No change	21,919	41,892	19,536	14,490	645	15,210	62,752	87,262	91,237	9263	364,205
Total land cover 1998	24,274	41,938	20,088	14,796	652	18,617	62,814	87,626	93,329	10,198	374,333

LCF2 → urban residential sprawl; LCF4 → agricultural internal conversion; LCF5 → conversion from forested and natural land to agricultural land; LCF6 → withdrawal of farming; LCF7 → forest creation and management; LCF9 → change due to natural and multiple causes (source: European Environment Agency). The time span of land stock is different between "LU1987–LU1998" and "Projected 2010–2050". By adjusting the amount of change to the same time span, the accounting results could be compared

a. LU1987 to LU1998



b. Projected 2010 to projected 2050



(LCF2, LCF4, and LCF9 are not presented here due to no change in land demand in the process of future projection.)

NOTE:
LCF2→ Urban residential sprawl; LCF4→ Agriculture internal conversions; LCF5→ Conversion from forested and natural land to agriculture; LCF6→ Withdrawal of farming; LCF7→ Forests creation and management; LCF9 →Change due to natural and multiple causes (Source: European Environment Agency, 2006. Land Accounts for Europe 1990-2000: Towards Integrated Land and Ecosystem Accounting)

Fig. 3 The spatial proportion of land change flow (LCF) for the periods of 1987–1998 and projected 2010–2050, calculating and mapping with the unit of 1947 local authorities

The patterns of net change and turnover exhibited similar trends, reflecting the influence of land demand settings. It is important to note that, although land demand is controlled by these settings, land allocation is determined by transition potentials derived from past land use changes, offering valuable insights into regional land use alterations (Guzman et al. 2020). It must be noticed that the accounting result spanned four decades; thus, it is inappropriate to compare it with LU1–LU2 without adjusting the time span.

Table 6 lists the projected land flows between 2010 and 2050. The LCM projected land use for these years under the influence of the land demand. According to this land demand, land cover flows such as LCF2, LCF4, and LCF9 were projected to maintain a 0 km^2 change throughout this period. In contrast, LCF6 showed considerable activity,

Table 6 Land flow accounting describing the projected future land cover changes from 2010 to 2050

(Unit: km^2)	RES	PAD	CRP	OAL	ABF	GRS	NFR	SFR	PFR	OLU	Total
LCF2	0	0	0	0	0	0	0	0	0	0	0
LCF4	0	0	0	0	0	0	0	0	0	0	0
LCF5	0	0	0	0	0	0	0	427	0	0	427
LCF6	0	7775	4939	3224	0	0	0	0	0	0	15,938
LCF7	0	0	0	0	0	0	0	438	617	0	1055
LCF9	0	0	0	0	0	0	0	0	0	0	0
Total consumption of 2010 land cover	0	7775	4939	3224	0	0	0	865	617	0	17,419
No change	24,214	31,808	13,647	10,637	3655	18,572	62,726	87,165	94,007	10,071	356,503
Total land cover 2010	24,214	39,584	18,585	13,861	3655	18,572	62,726	88,029	94,623	10,071	373,922
LCF2	0	0	0	0	0	0	0	0	0	0	0
LCF4	0	0	0	0	0	0	0	0	0	0	0
LCF5	0	0	0	156	271	0	0	0	0	0	427
LCF6	0	0	0	0	9556	0	0	1774	4608	0	15,938
LCF7	0	0	0	0	0	0	0	617	438	0	1055
LCF9	0	0	0	0	0	0	0	0	0	0	0
Total formation of 2050 land cover	0	0	0	156	9826	0	0	2391	5046	0	17,419
No change	24,214	31,808	13,647	10,637	3655	18,572	62,726	87,165	94,007	10,071	356,503
Total land cover 2050	24,214	31,808	13,647	10,793	13,482	18,572	62,726	89,555	99,053	10,071	373,922

LCF2 → urban residential sprawl; LCF4 → agricultural internal conversion; LCF5 → conversion from forested and natural land to agriculture; LCF6 → withdrawal of farming; LCF7 → forest creation and management; LCF9 → change due to natural and multiple causes (source: European Environment Agency, 2006). Environment Agency. The time span of land stock is different between "LU1987–LU1998" and "Projected 2010–2050". By adjusting the amount of change to the same time span, the accounting results could be compared

with paddy fields experiencing the largest consumption (7775 km^2), followed by cropland (4939 km^2) and other agricultural land (3224 km^2). Most of this consumption was expected to transition into abandoned farmland (9556 km^2), with secondary forest (1774 km^2) and plantation forest (4608 km^2) showing notable increases.

Figure 3b illustrates the geographic distribution of these changes in Japan. The farmland abandonment trend (LCF6) is widespread but is particularly pronounced in local authorities in Hokkaido and the center of the Kanto region. LCF5 and LCF7 exhibited changes in land flow, albeit to a lesser extent than LCF6. Geographically, agricultural reclamation (LCF5) was more likely to occur in northern Kyusyu and Hokkaido, while internal forest management (LCF7) was more prevalent among local authorities in south Kyusyu and north Tohoku (Fig. 3b).

Discussion

Analysis of land stock and flow accounts in the context of the socioeconomic background from 1987–1998

The analysis of land stock and flow accounts from 1987 to 1998 revealed that urban residential sprawl and forest management were major issues during this period and were closely intertwined with historical socioeconomic and regional development dynamics. The average gross domestic product growth rate in this period was maintained at 6% in the early half, dropping to 1% in the latter half. This represents the change in Japan's socioeconomic status (Cabinet Office 2008).

Urban residential sprawl was particularly notable among local authorities around Tokyo and Osaka, Japan's most densely populated urban centers. Driven by population growth and an increasing number of households (National Institute of Population and Social Security Research 2017), the demand for urban land resources is continuing to increase. This trend has led to extensive urban sprawl, distinct from European patterns where agricultural land is often consumed; in Japan, forests are predominantly converted (EEA 2006). Secondary forest, which is integral to Japan's rural landscape and biodiversity (Kobori and Primack 2003; Takeuchi et al. 2016), has been particularly affected. Despite their ecological importance (Kadoya and Washitani 2011; Morimoto 2011), these forests have become the prime targets of urban development, as these human-familiar forests have a high potential for residential development, thus threatening biodiversity within secondary forests (Ohsawa 2004; Saito 2004; Katoh et al. 2009). Japan's national urban policies have played a critical role in the growth of major cities, such as Tokyo and Osaka (Abe et al. 2018; Sorensen 2019). While urban development is necessary, it has had major impacts on environmentally significant land resources and culturally important secondary forest (Kohsaka et al. 2021).

The land stock account demonstrated substantial declines in secondary and natural forests, whereas grassland and plantation areas increased. In Hokkaido, which had the highest proportion of natural forest among all regions (67.0%) (Hokkaido Prefecture 2011), there was a notable decrease in natural forest, which coincided with increases in grassland, cropland, and residential land. As Hokkaido contributes over 22.5% of Japan's total agricultural output, primarily in livestock production, making it the leading production region (Department of Agriculture Hokkaido Government 2020), increased grassland and cropland are likely linked to the livestock industry's growth. Figure 3a illustrates the robust activities in reclamation and forest management by several local authorities in Hokkaido.

Forest management practices have undergone a dramatic transition in northwestern Tohoku. A detailed examination of these transitions revealed that the conversion of secondary forests into plantation forests in these areas was driven by high-timber shipments. Interestingly, over 40% of the grassland originated from previous cut-over forests designated for replanting as plantation forests. However, declining timber prices and rising labor costs have reduced the profitability of the forestry industry (Hayajiri 2009). Imported timber and wood products have been used to counteract the decrease in wood production, leading to reduced investment in restoration efforts (Forestry Agency of MAFF 2018). To break this cycle of low wood self-sufficiency, some cut-over grasslands were intentionally allowed to undergo natural vegetation succession after clear-cutting, which contributed considerably to the extensive increase in grassland observed from LU1987 to LU1998.

Regarding the land flow changes caused by natural and multiple causes (LCF9), more than 9 km^2 of land use were converted to 'other land use' in LU1998, primarily consisting of water bodies, with golf courses following as the next major category. During this period, the quantity of water bodies remained relatively stable, while golf course construction exhibited a continuous upward trend (Kita 2012). The decline in secondary and natural forests appears to coincide with the establishment of golf courses. The early 1990s was a major turning point in Japan's extended economic recession. The land use changes observed from LU1987 to LU1998 echo the remnants of the country's economic development during this period (Shoyama and Braimoh 2011).

Balancing land use by 2050: addressing farmland abandonment and forest conservation.

Comparing the LCM projection results with previous research (Shoyama et al. 2019, 2021), the trend of decreasing agricultural land and no change in residential land is the same. However, in Shoyama's study, abandoned farmland increased by 0.23% under the BaU scenario, which is much lower than the amount (3.6%) in this study. This is because, in Shoyama's study, parts of the abandoned farmland were converted into the plantation forest and grassland categories. Grassland and plantation forest showed considerable increases by 2050. However, in this study, large parts of abandoned farmland remained in the same category by 2050.

Based on the projected land stock, there was a decline in agricultural land, with Hokkaido and Kyushu facing major challenges due to farmland abandonment. Hokkaido, which comprises one-quarter of Japan's agricultural land area, is projected to experience the highest proportion of abandoned farmland by 2050 (Kobayashi et al. 2020). A closer examination of the geographic patterns (Fig. 3b) reveals that the local authorities in central Hokkaido show a pronounced trend in the flow of "withdrawal of farming." This region, historically characterized by peatlands, saw these wetlands transform into arable land, particularly paddy fields. Peatlands that were initially unsuitable for cultivation owing to their wet and marshy conditions were extensively drained and improved over time to support agricultural activities (Umeda and Inoue 1995). However, the drainage of peatlands has had environmental consequences, such as carbon release, fertile soil loss, and substantial land subsidence (Hatano et al. 2005; Joosten 2015; Naser et al. 2018). Peatlands store twice the amount of carbon as forests (Joosten 2015) and are thus crucial for carbon sequestration and controlling global greenhouse gases (Akumu and McLaughlin 2014). Given their environmental importance, peatland restoration is now recognized as a critical global environmental goal (Humpender et al. 2020; Tanneberger et al. 2021; Strack et al. 2022). The restoration of abandoned farmland, particularly that located in former peatland areas, to peatlands capitalizes on their inherent capacity for carbon storage. By offering a strategic solution to land management and environmental conservation challenges, this approach aligns well with development goals (Seifollahi-Aghmiuni et al. 2019; Tanneberger et al. 2021; O'Neill et al. 2022).

There is a clear concentration of farmland abandonment by local authorities within Tohoku and Kanto, as evidenced by the increasing trend shown in Fig. 3b. These regions are central to Japan's agricultural sector, suggesting a higher potential for farmland abandonment. Farmland abandonment is not unique to Japan, but a global issue (Huang et al. 2020; Subedi et al. 2022). Unlike the USA, Japan shares similar underlying causes with the European Union (EU). In the EU, factors such as the aging of farmers, lack of agricultural labor, low agricultural income, and issues with physical farm structures have been identified as key drivers of farmland abandonment (Keenleyside and Tucker 2010; Hatna and Bakker

2011; Terres et al. 2015; Levers et al. 2018). In Japan, similar trends have been observed, particularly in the aging farming population and agricultural labor shortages, which are expected to intensify owing to ongoing depopulation (Kitano 2021; Sasaki et al. 2021). Recent policy initiatives have increasingly focused on revitalizing abandoned farmland (Kohsaka and Kohyama 2022; Nishi 2022). Although farmland abandonment poses major challenges, it presents opportunities to promote sustainable land use practices in the future (Long et al. 2021; Fayet et al. 2022). Strategies such as reforestation or restoration of wetlands and peatlands on abandoned lands are being considered (Hamman 2019; Mameno and Kubo 2022). Such initiatives are expected to contribute positively, particularly in enhancing biodiversity conservation and aiding climate change mitigation efforts (Strack et al. 2022).

In Hokkaido and Kyushu, the conversion of forested and natural land into agricultural areas is projected to be relatively frequent. According to a detailed examination of the types of land conversion, the rate of farmland abandonment exceeds that of currently active agricultural land, indicating that forest conversion and management needs to be addressed in the future. Hokkaido is projected to experience a high level of farmland abandonment along with numerous possibilities for land reclamation. For Hokkaido's land use planning, forest conservation and the concurrent repurposing of abandoned farmland should be considered, with the aim of promoting sustainable development (Frei et al. 2022; Fayet 2023). Changes in land use, particularly concerning the creation and management of forests, are of great importance to various local authorities, particularly those in northern Tohoku and southern Kyushu. The land flow of forest creation and management is tied to one definition in the EEA indicator; natural, secondary, and plantation forests are not separated. Tree species with high utility value are planted in plantation forests, such as Cedar or Hinoki, which has damaged the biodiversity of original broadleaf forest ecosystems (Nagaike 2000; Niiyama et al. 2010; Shimada et al. 2018). Forest management challenges and appropriate management methods are regionally dependent. Projections for future land use in Kyushu suggest an increase in secondary forests by 2050, which could enhance biodiversity. In contrast, Tohoku is expected to witness considerable growth in plantation forests during the same period. These plantation forests, primarily intended to serve the wood industry, and secondary forests, designated for semi-natural conservation, present complex tradeoffs. Identifying the optimal balance between these two forest land use types is crucial for sustainable environmental management and economic development.

Limitations and the way forward

This study had several limitations. The first pertains to the absence of recent data. Land use data with an independent category of abandoned farmland should be obtained. We used data from the National Vegetation Survey. Although these datasets are broadly recognized and used within Japan, they are produced at five-year intervals and cover only three time periods; the latest data are incomplete at the time point of March 2024. This temporal framework restricts our ability to accurately track and analyze land use trends. This study's projections were based on the most comprehensive data currently available. To enhance the robustness of future analyses, we recommend generating updated land use data using contemporary nationwide satellite data. The second limitation is this study's exclusive focus on a BaU scenario. Future research should explore alternative scenarios that include strategies for abandoned land rehabilitation, thereby providing a broader perspective on potential land use dynamics. Finally, quantifying abandoned farmland presents its own set of challenges, largely due to limited spatial information (Lasanta et al. 2015; Kobayashi et al. 2020). In many cases, fields that were once cultivated underwent vegetative succession, rendering them less recognizable (Feranec et al. 2010). Additional complications arise in the spatial mapping and monitoring of land-abandonment processes. These include potential discrepancies in scale mismatches between the units used for monitoring and those used for land management, issues with LULC classification accuracy, and variations in reporting agricultural practices (Su et al. 2018). Addressing these challenges is crucial for enhancing the precision and applicability of future land use studies.

Conclusion

In this study, we conducted land accounting analysis from 1987 to 1998 to evaluate Japan's land resources, employing both land stock and flow metrics in conjunction with EEA indicators to elucidate the interplay between land resources and socioeconomic factors. During this period, we observed considerable LULC transitions, including urban expansion and a decline in natural and secondary forests, leading to increases in grassland and plantation forests. These shifts are primarily driven by economic and population growth dynamics. Furthermore, Japan has been witnessing a depopulation trend since 2009, introducing new complexities into land use dynamics, with the precise geographic implications of this trend remaining unclear. To address this, we projected land use patterns for 2050 at a high spatial resolution, reflecting the anticipated decrease in demand for developed land at a national scale. The combination of land accounting and land change projections reveals that farmland abandonment is likely to become a pervasive issue across Japan, with acute impacts in specific regions, notably Hokkaido and Kanto. Abandoned farmlands present opportunities for natural restoration. The land use projection model developed in this study represents a major contribution to scenario analysis at the national level. It offers high-resolution insights that are crucial for various applications, including ecosystem service assessment, agriculture, resource management, disaster risk reduction, and climate change scenario projections. This high-resolution analysis is especially important in discussing farmland abandonment in Japan. Land abandonment is not an unique issue in Japan; it is attracting attention internationally. This study can contribute to future modeling in farmland abandonment research.

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Data availability The data that support the findings of this study are available on request from the corresponding author, Wanhui Huang. The data are not publicly available due to the high resolution land use map that could compromise the privacy of residence location information.

Declarations

Conflict of interest The authors declare no conflicts of interest.

References

Abe K, Kubo T, Komaki N (2018) International and transnational perspectives on urban systems. Adv Geogr Environ Sci. https://doi.org/10.1007/978-981-10-7799-9_7

Akashi N, Nakashizuka T (1999) Effects of bark-stripping by Sika deer (*Cervus nippon*) on population dynamics of a mixed forest in Japan. For Ecol Manag 113:75–82. https://doi.org/10.1016/s0378-1127(98)00415-0

Akumu CE, McLaughlin JW (2014) Modeling peatland carbon stock in a delineated portion of the Nayshkootayaow river watershed in Far North, Ontario using an integrated GIS and remote sensing approach. CATENA 121:297–306. https://doi.org/10.1016/j.catena.2014.05.025

Atkinson PM, Tatnall ARL (1997) Introduction neural networks in remote sensing. Int J Remote Sens 18:699–709. https://doi.org/10.1080/014311697218700

Bala G, Caldeira K, Wickett M, Phillips TJ, Lobell DB, Delire C, Mirin A (2007) Combined climate and carbon-cycle effects of large-scale deforestation. Proc Natl Acad Sci 104:6550–6555. https://doi.org/10.1073/pnas.0608998104

Báldi A, Batáry P (2011) The past and future of farmland birds in Hungary. Bird Study 58:365–377. https://doi.org/10.1080/00063657.2011.588685

Bariamis G, Paschos G, Baltas E (2018) Land Accounts in the river basin districts of Greece. Environ Process 5:213–237. https://doi.org/10.1007/s40710-018-0321-8

Benefoh DT, Villamor GB, van Noordwijk M, Borgemeister C, Asante WA, Asubonteng KO (2018) Assessing land use typologies and change intensities in a structurally complex Ghanaian cocoa landscape. Appl Geogr 99:109–119. https://doi.org/10.1016/j.apgeog.2018.07.027

Bringezu S, O'Brien M, Schütz H (2012) Beyond biofuels: assessing global land use for domestic consumption of biomass. Land Policy 29:224–232. https://doi.org/10.1016/jlandusepol.2011.06.010

Bruckner M, Fischer G, Tramberend S, Giljum S (2015) Measuring telecouplings in the global land system: a review and comparative evaluation of land footprint accounting methods. Ecol Econ 114:11–21. https://doi.org/10.1016/j.ecolecon.2015.03.008

Burnham BO (1973) Markov intertemporal land use simulation model. J Agric Appl Econ 5:253–258. https://doi.org/10.1017/s0081305200011110

Cabinet Office (2008) GDP statistics(16)~(66). (in Japanese) https://www5.cao.go.jp/j-j/wp/wp-je08/08b09010.html. Accessed 6 June 2024

Department of Agriculture Hokkaido Government (2020) Agriculture in Hokkaido Japan. https://www.pref.hokkaido.lg.jp/fs/2/3/7/6/7/7/5/_/genjyou_english_0206.pdf. Accessed 6 June 2024

Eastman JR, Jin, et al (1995) Raster procedures for multi-criteria/multi-objective decisions. Photogram Eng Remote Sens 61:539–547

Eastman JR (2016) TerrSet manual. Clark University, Worcester

EEA (2006) Land Accounts for Europe 1990–2000: towards integrated land and ecosystem accounting. European Environment Agency

Fayet CMJ (2023) From challenges to opportunities in abandoned farmlands. https://doi.org/10.5463/thesis.355

Fayet CMJ, Reilly KH, Ham CV, Verburg PH (2022) What is the future of abandoned agricultural lands? A systematic review of alternative trajectories in Europe. Land Policy 112:105833. https://doi.org/10.1016/jlandusepol.2021.105833

Feranec J, Jaffrain G, Soukup T, Hazeu G (2010) Determining changes and flows in European landscapes 1990–2000 using CORINE land cover data. Appl Geogr 30:19–35. https://doi.org/10.1016/j.apgeog.2009.07.003

Foley JA, DeFries R, Asner GP, Barford C, Bonan G, Carpenter SR, Chapin FS, Coe MT, Daily GC, Gibbs HK, Helkowski JH, Holloway T, Howard EA, Kucharik CJ, Monfreda C, Patz JA, Prentice IC, Ramankutty N, Snyder PK (2005) Global consequences of land use. Science 309:570–574. https://doi.org/10.1126/science.1111772

Forestry Agency of Ministry of Agriculture Forestry and Fisheries (FAMAFF) (2018) Annual Report on Forest and Forestry in

Japan. (in Japanese) https://www.rinya.maff.go.jp/j/kikaku/hakusyo/30hakusyo_h/all/chap4_1_2.html. Accessed 6 June 2024

Frei T, Edou K, Fernández-Blanco CR, Winkel G (2022) Governing abandoned land: storylines on natural forest regrowth in France and Spain. Environ Sci Policy 135:58–66. https://doi.org/10.1016/j.envsci.2022.04.022

Gibson L, Münch Z, Palmer A, Mantel S (2018) Future land cover change scenarios in South African grasslands—implications of altered biophysical drivers on land management. Heliyon 4:e00693. https://doi.org/10.1016/j.heliyon.2018.e00693

Guzman LA, Escobar F, Peña J, Cardona R (2020) A cellular automata-based land use model as an integrated spatial decision support system for urban planning in developing cities: the case of the Bogotá region. Land Policy 92:104445. https://doi.org/10.1016/jlandusepol.2019.104445

Haines-Young R (2009) Land use and biodiversity relationships. Land Policy 26:S178–S186. https://doi.org/10.1016/jlandusepol.2009.08.009

Hamman E (2019) Wetland restoration in Japan: what's law got to do with It? New Voices Jpn Stud 11:47–73. https://doi.org/10.21159/nvjs.11.03

Hashimoto S, DasGupta R, Kabaya K, Matsui T, Haga C, Saito O, Takeuchi K (2018) Scenario analysis of land use and ecosystem services of social-ecological landscapes: implications of alternative development pathways under declining population in the Noto Peninsula, Japan. Sustain Sci 14:1–23. https://doi.org/10.1007/s11625-018-0626-6

Hatano HM, Nagata O, Hatano R (2005) Greenhouse gas fluxes and global warming potentials in crop fields on soil-dressed peatland in Hokkaido, Japan. Phyton 45:285–293

Hatna E, Bakker MM (2011) Abandonment and expansion of arable land in Europe. Ecosystems 14:720–731. https://doi.org/10.1007/s10021-011-9441-y

Hayajiri M (2009) Recent trends in forest labour studies and their related fields since the late 1990s in Japan: review and future challenges. J Sci Labour 85:191–201

Hernández-Blanco M, Costanza R, Chen H, de Groot D, Jarvis D, Kubiszewski I, Montoya J, Sangha K, Stoekl N, Turner K, van't Hoff V (2022) Ecosystem health, ecosystem services, and the well-being of humans and the rest of nature. Glob Change Biol 28:5027–5040. https://doi.org/10.1111/gcb.16281

Hokkaido Prefecture (2011) Hokkaido data book 2011. (in Japanese) https://www.pref.hokkaido.lg.jp/ss/tkk/databook/. Accessed 6 June 2024

Huang Y, Fengqin L, Hualin X (2020) A scient metrics review on farmland abandonment research. Land 9(8):263. https://doi.org/10.3390/land9080263

Huang W, Hashimoto S, Yoshida T, Saito O, Taki K (2021) A nature-based approach to mitigate flood risk and improve ecosystem services in Shiga, Japan. Ecosyst Serv 50:101309. https://doi.org/10.1016/j.ecoser.2021.101309

Humpender F, Karstens K, Lotze-Campen H et al (2020) Peatland protection and restoration are key for climate change mitigation. Environ Res Lett 15:104093. https://doi.org/10.1088/1748-9326/abae2a

Imai N, Otokawa H, Okamoto A, Yamazaki K, Tamura T, Sakagami T, Ishizaka S, Shinojima H (2023) Abandonment of cropland and seminatural grassland in a mountainous traditional agricultural landscape in Japan. Sustainability 15:7742. https://doi.org/10.3390/su15107742

IPBES (2019) Summary for policymakers of the global assessment report on biodiversity and ecosystem services. Biodivers Ecosyst Serv. https://doi.org/10.5281/zenodo.3553579

Ivanov E, Eigenraam M (2017) Land accounts and ecosystem extent. https://seea.un.org/sites/seea.un.org/files/land_accounts_and_ecosystem_extent.pdf. Accessed 6 June 2024

Joosten H (2015) Peatlands, climate change mitigation and biodiversity conservation. Nord Counc Minist. https://doi.org/10.6027/anp2015-727

Kadoya T, Washitani I (2011) The Satoyama Index: a biodiversity indicator for agricultural landscapes. Agric Ecosyst Environ 140:20–26. https://doi.org/10.1016/j.agee.2010.11.007

Kamaraj M, Rangarajan S (2022) Predicting the future land use and land cover changes for Bhavani basin, Tamil Nadu, India, using QGIS MOLUSCE plugin. Environ Sci Pollut Res 29:86337–86348. https://doi.org/10.1007/s11356-021-17904-6

Kastner T, Schaffartzik A, Eisenmenger N, Erb K-H, Haberl H, Krausmann F (2014) Cropland area embodied in international trade: contradictory results from different approaches. Ecol Econ 104:140–144. https://doi.org/10.1016/j.ecolecon.2013.12.003

Katoh K, Sakai S, Takahashi T (2009) Factors maintaining species diversity in satoyama, a traditional agricultural landscape of Japan. Biol Conserv 142:1930–1936. https://doi.org/10.1016/j.biocon.2009.02.030

Keenleyside C, Tucker GM (2010) Farmland abandonment in the EU: an assessment of trends and prospects. Report prepared for WWF London

Kertész Á, Nagy L, Balázs B (2019) Effect of land use change on ecosystem services in Lake Balaton Catchment. Land Use Policy 80:430–438. https://doi.org/10.1016/jlandusepol.2018.04.005

Kita M (2012) The situation of Golf in Japan. JCA J 18:1–6

Kitano S (2021) Estimation of determinants of farmland abandonment and its data problems. Land 10:596. https://doi.org/10.3390/land10060596

Kobayashi Y, Higa M, Higashiyama K, Nakamura F (2020) Drivers of land use changes in societies with decreasing populations: a comparison of the factors affecting farmland abandonment in a food production area in Japan. PLoS One 15:e0235846. https://doi.org/10.1371/journal.pone.0235846

Kobori H, Primack RB (2003) Participatory conservation approaches for satoyama, the traditional forest and agricultural landscape of Japan. AMBIO A J Hum Environ 32:307–311. https://doi.org/10.1579/0044-7447-032.4.307

Kohsaka R, Kohyama S (2022) State of the art review on land use policy: changes in forests, agricultural lands and renewable energy of Japan. Land 11:624. https://doi.org/10.3390/land11050624

Kohsaka R, Ito K, Miyake Y, Uchiyama Y (2021) Cultural ecosystem services from the afforestation of rice terraces and farmland: emerging services as an alternative to monoculturalization. For Ecol Manag 497:119481. https://doi.org/10.1016/j.foreco.2021.119481

Kolar J (2001) Land cover accounting. Int J Environ Pollut 15:695. https://doi.org/10.1504/ijep.2001.004988

Kumar SS (2011) Land accounting in India: Issues and concerns. Central Statistics Office, Ministry of Statistics & Programme Implementation, New Delhi, India

Lasanta T, Nadal-Romero E, Arnáez J (2015) Managing abandoned farmland to control the impact of re-vegetation on the environment. The state of the art in Europe. Environ Sci Policy 52:99–109. https://doi.org/10.1016/j.envsci.2015.05.012

Levers C, Schneider M, Prishchepov AV, Estel S, Kuemmerle T (2018) Spatial variation in determinants of agricultural land abandonment in Europe. Sci Total Environ 644:95–111. https://doi.org/10.1016/j.scitotenv.2018.06.326

Li S, Li X (2017) Global understanding of farmland abandonment: a review and prospects. J Geogr Sci 27:1123–1150. https://doi.org/10.1007/s11442-017-1426-0

Lindborg R, Eriksson O (2004) Effects of restoration on plant species richness and composition in Scandinavian semi-natural grasslands. Restor Ecol 12:318–326. https://doi.org/10.1111/j.1061-2971.2004.00334.x

Liu Y, Zhou Y (2021) Reflections on China's food security and land use policy under rapid urbanization. Land Policy 109:105699. https://doi.org/10.1016/jlandusepol.2021.105699

Liu X, Xu Y, Engel BA, Sun S, Zhao X, Wu P, Wang Y (2021) The impact of urbanization and aging on food security in developing countries: the view from Northwest China. J Clean Prod 292:126067. https://doi.org/10.1016/j.jclepro.2021.126067

Long H, Zhang Y, Ma L, Tu S (2021) Land use transitions: progress, challenges and prospects. Land 10:903. https://doi.org/10.3390/land10090903

Ma A (2005) Environmental degradation and human well-being: report of the millennium ecosystem assessment. Popul Dev Rev 31:389–398. https://doi.org/10.1111/j.1728-4457.2005.00073.x

MacDonald D, Crabtree JR, Wiesinger G, Dax T, Stamou N, Fleury P, Lazpita JG, Gibon A (2000) Agricultural abandonment in mountain areas of Europe: environmental consequences and policy response. J Environ Manag 59:47–69. https://doi.org/10.1006/jema.1999.0335

Mameno K, Kubo T (2022) Socio-economic drivers of irrigated paddy land abandonment and agro-ecosystem degradation: evidence from Japanese agricultural census data. PLoS One 17:e0266997. https://doi.org/10.1371/journal.pone.0266997

Matsui T, Ugata T, Machimura T (2014) A development of factor analyzing and predicting model of abandoned agricultural land with machine learning algorisms. J Jpn Soc Civ Eng Ser G 70:131–139. https://doi.org/10.2208/jscejer.70.ii_131

Mauerhofer V, Ichinose T, Blackwell BDD et al (2018) Underuse of social-ecological systems: a research agenda for addressing challenges to biocultural diversity. Land Use Policy 72:57–64. https://doi.org/10.1016/jlandusepol.2017.12.003

Ministry of Agriculture Forestry and Fisheries (MAFF) (2010) Census of agriculture and forestry. https://www.cao.go.jp/sasshin/kiseiseido/meeting/2011/agri/120712/item2-2_2.pdf

Ministry of Agriculture Forestry and Fisheries (MAFF) (2016) Current situation and countermeasures for abandoned farmland. (in Japanese) https://www5.cao.go.jp/keizai-shimon/kaigi/special/2030tf/281114/shiryou1_2.pdf. Accessed 6 June 2024

Ministry of the Environment (2007) The third national biodiversity strategy of Japan. https://www.biodic.go.jp/biodiversity/about/initiatives3/files/nbsap_e/TheThirdNBS.pdf. Accessed 6 June 2024

Ministry of the Environment (2021) Japan biodiversity outlook 3, 2021 Report of comprehensive assessment of biodiversity and ecosystem services in Japan. https://www.biodic.go.jp/biodiversity/activity/policy/jbo3/generaloutline/files/JBO3_pamph_en.pdf. Accessed 6 June 2024

Mishra VN, Rai PK (2016) A remote sensing aided multi-layer perceptron-Markov chain analysis for land use and land cover change prediction in Patna district (Bihar), India. Arab J Geosci 9:249. https://doi.org/10.1007/s12517-015-2138-3

Mitsuda Y, Ito S (2011) A review of spatial-explicit factors determining spatial distribution of land use/land use change. Landsc Ecol Eng 7:117–125. https://doi.org/10.1007/s11355-010-0113-4

Morimoto Y (2011) What is Satoyama? Points for discussion on its future direction. Landsc Ecol Eng 7:163–171. https://doi.org/10.1007/s11355-010-0120-5

Nagaike T (2000) A review of ecological studies on plan species diversity in plantation ecosystems. J Jpn for Soc 82:407–416

Nagaike T (2020) Effects of heavy, repeated bark stripping by *Cervus nippon* on survival of *Abies veitchii* in a subalpine coniferous forest in central Japan. J for Res 31:1139–1145. https://doi.org/10.1007/s11676-019-00940-x

Naser HM, Nagata O, Sultana S, Hatano R (2018) Impact of management practices on methane emissions from paddy grown on mineral soil over peat in Central Hokkaido, Japan. Atmosphere 9:212. https://doi.org/10.3390/atmos9060212

National Institute of Population and Social Security Research (2017) Population projections for Japan: 2016 to 2065 (in Japanese). Population Research Series, No. 336. http://www.ipss.go.jp/pp-zenkoku/j/zenkoku2017/pp29_ReportALL.pdf. Accessed 6 June 2024

Niiyama K, Ogawa M, Kushima H, Takahashi K, Sato T, Sakai T, Tauchi H (2010) Collection and evaluation of literatures related to broadleaf tree regeneration for leading artificial coniferous forests to broadleaf forests. J Jpn for Soc 92:292–296. https://doi.org/10.4005/jjfs.92.292

Nishi M (2022) Japanese land reform in the new era? Farmers' well-being and sustainable farmland management. Environ Plan C Politics Space 41:429–447. https://doi.org/10.1177/23996544221138711

Nishimwe G, Rugema DM, Uwera C, Graveland C, Stage J, Munyawera S, Ngabirame G (2020) Natural capital accounting for land in Rwanda. Sustainability 12:5070. https://doi.org/10.3390/su12125070

O'Neill EA, Bennett MM, Rowan NJ (2022) Peatland-based innovation can potentially support and enable the sustainable development goals of the United Nations: case study from the Republic of Ireland. Case Stud Chem Environ Eng 6:100251. https://doi.org/10.1016/j.cscee.2022.100251

Ogawa M, Mastuzaki S, Ishihama F (2020) Explanation of a comprehensive land use classification map of Japan based on the latest 1:25,000 vegetation map by the Ministry of the Environment. Jpn J Conserv Ecol 25:117–122. https://doi.org/10.18960/hozen.1908

Ohsawa M (2004) Species richness of Cerambycidae in larch plantations and natural broad-leaved forests of the central mountainous region of Japan. For Ecol Manag 189:375–385. https://doi.org/10.1016/j.foreco.2003.09.007

Olmedo MTC, Mas J-F, Paegelow M (2022) Validation of soft maps produced by a land use cover change model. In: García-Álvarez D, Olmedo MTC, Paegelow M, Mas JF (eds) Land use cover datasets and validation tools. Springer, Cham, pp 189–203. https://doi.org/10.1007/978-3-030-90998-7_10

Parra-Paitan C, Verburg PH (2022) Accounting for land use changes beyond the farm-level in sustainability assessments: the impact of cocoa production. Sci Total Environ 825:154032. https://doi.org/10.1016/j.scitotenv.2022.154032

Parsamehr K, Gholamalifard M, Kooch Y (2020) Comparing three transition potential modeling for identifying suitable sites for REDD+ projects. Spat Inf Res 28:159–171. https://doi.org/10.1007/s41324-019-00273-1

Pontius RG, Shusas E, McEachern M (2004) Detecting important categorical land changes while accounting for persistence. Agric Ecosyst Environ 101:251–268. https://doi.org/10.1016/j.agee.2003.09.008

Poschlod P, Bakker JP, Kahmen S (2005) Changing land use and its impact on biodiversity. Basic Appl Ecol 6:93–98. https://doi.org/10.1016/j.baae.2004.12.001

Queiroz C, Beilin R, Folke C, Lindborg R (2014) Farmland abandonment: threat or opportunity for biodiversity conservation? A global review. Front Ecol Environ 12:288–296. https://doi.org/10.1890/120348

Saito O (2004) Quantitative and spatial changes in woodland vegetation for the last 40 years in the Kanto region, Japan. Theory Appl GIS 12:145–154. https://doi.org/10.5638/thagis.12.145

Sasaki K, Hotes S, Ichinose T, Doko T, Wolters V (2021) Hotspots of agricultural ecosystem services and farmland biodiversity overlap with areas at risk of land abandonment in Japan. Land 10:1031. https://doi.org/10.3390/land10101031

Seifollahi-Aghmiuni S, Nockrach M, Kalantari Z (2019) The potential of wetlands in achieving the sustainable development goals of the 2030 agenda. Water 11:609. https://doi.org/10.3390/w11030609

Shimada K, Toshio K, Ohnaka M, Kojiro I (2018) Changes of plant diversity and species composition with reference to habitat classification in recovered broad-leaved secondary forest in abandoned plantation forest after meteorological disturbance in the warm-temperate zone. J for Environ 60:11–21. https://doi.org/10.18922/jjfe.60.1_11

Shoyama K (2021) Assessment of land use scenarios at a national scale using intensity analysis and figure of merit components. Land 10:379. https://doi.org/10.3390/land10040379

Shoyama K, Braimoh AK (2011) Analyzing about sixty years of land-cover change and associated landscape fragmentation in Shiretoko Peninsula, Northern Japan. Landsc Urban Plan 101:22–29. https://doi.org/10.1016/j.landurbplan.2010.12.016

Shoyama K, Matsui T, Hashimoto S, Kabaya K, Oono A, Saito O (2019) Development of land use scenarios using vegetation inventories in Japan. Sustain Sci 14:39–52. https://doi.org/10.1007/s11625-018-0617-7

Shoyama K, Nishi M, Hashimoto S, Saito O (2021) Outcome-based assessment of the payment for mountain agriculture: a community-based approach to countering land abandonment in Japan. Environ Manag 68:353–365. https://doi.org/10.1007/s00267-021-01497-4

Smith R (2007) Development of the SEEA 2003 and its implementation. Ecol Econ 61:592–599. https://doi.org/10.1016/j.ecolecon.2006.09.005

Smith P, Milne R, Powlson DS, Smith JU, Falloon P, Coleman K (2000) Revised estimates of the carbon mitigation potential of UK agricultural land. Soil Manag 16:293–295. https://doi.org/10.1111/j.1475-2743.2000.tb00214.x

Sorensen A (2019) The making of urban Japan, cities and planning from Edo to the twenty first century. Ecol Econ. https://doi.org/10.4324/9780203993927

Strack M, Davidson SJ, Hirano T, Dunn C (2022) The potential of peatlands as nature-based climate solutions. Curr Clim Change Rep 8:71–82. https://doi.org/10.1007/s40641-022-00183-9

Su G, Okahashi H, Chen L (2018) Spatial pattern of farmland abandonment in Japan: identification and determinants. Sustainability 10:3676. https://doi.org/10.3390/su10103676

Subedi YR, Kristiansen P, Cacho O (2022) Drivers and consequences of agricultural land abandonment and its reutilisation pathways: a systematic review. Environ Dev 42:100681. https://doi.org/10.1016/j.envdev.2021.100681

Taelman SE, Schaubroeck T, Meester SD, Boone L, Dewulf J (2016) Accounting for land use in life cycle assessment: the value of NPP as a proxy indicator to assess land use impacts on ecosystems. Sci Total Environ 550:143–156. https://doi.org/10.1016/j.scitotenv.2016.01.055

Takatsuki S (2009) Effects of sika deer on vegetation in Japan: a review. Biol Conserv 142:1922–1929. https://doi.org/10.1016/j.biocon.2009.02.011

Takeuchi K, Ichikawa K, Elmqvist T (2016) Satoyama landscape as social–ecological system: historical changes and future perspective. Curr Opin Environ Sustain 19:30–39. https://doi.org/10.1016/j.cosust.2015.11.001

Tanneberger F, Appulo L, Ewert S, Lakner S, Brolcháin NÓ, Peters J, Wichtmann W (2021) The power of nature-based solutions: how peatlands can help us to achieve key EU sustainability objectives. Adv Sustain Syst 5:2000146. https://doi.org/10.1002/adsu.202000146

Terres J-M, Scacchiafichi LN, Wania A, Ambar M, Anguiano E, Buckwell A, Coppola A, Gocht A, Källström HN, Pointereau P, Strijker D, Visek L, Vranken L, Zobena A (2015) Farmland abandonment in Europe: identification of drivers and indicators, and development of a composite indicator of risk. Land Use Policy 49:20–34. https://doi.org/10.1016/jlandusepol.2015.06.009

Uchida K, Ushimaru A (2014) Biodiversity declines due to abandonment and intensification of agricultural lands: patterns and mechanisms. Ecol Monogr 84:637–658. https://doi.org/10.1890/13-2170.1

Umeda Y, Inoue T (1995) Conservation of mire wetland in Hokkaido. J Agric Eng Soc Jpn 63:249–254. https://doi.org/10.11408/jjsidre1965.63.3_249

UN (2014) System of environmental-economic accounting 2012. United Nations

UN, European Commission, International Monetary Fund, Organisation for Economic Co-operation and Development, World Bank (2003) Integrated environmental and economic accounting 2003. United Nations

UNU (2010) Japan Satoyama Satoumi Assessment, 2010, Satoyama-Satoumi Ecosystems and Human Well-being: Socio-ecological Production Landscapes of Japan—Summary for Decision Makers. United Nations University, Tokyo

Ustaoglu E, Collier MJ (2018) Farmland abandonment in Europe: an overview of drivers, consequences, and assessment of the sustainability implications. Environ Rev 26:396–416. https://doi.org/10.1139/er-2018-0001

van der Zanden EH, Verburg PH, Schulp CJE, Verkerk PJ (2017) Trade-offs of European agricultural abandonment. Land Use Policy 62:290–301. https://doi.org/10.1016/jlandusepol.2017.01.003

Weber J-L (2007) Implementation of land and ecosystem accounts at the European Environment Agency. Ecol Econ 61:695–707. https://doi.org/10.1016/j.ecolecon.2006.05.023

Wentland SA, Ancona ZH, Bagstad KJ, Boyd J, Hass JL, Gindelsky M, Moulton JG (2020) Accounting for land in the United States: integrating physical land cover, land use, and monetary valuation. Ecosyst Serv 46:101178. https://doi.org/10.1016/j.ecoser.2020.101178

Yoshihara S (2017) Realities and challenges of land issues in the era of depopulation. Jpn J Real Estate Sci 31:79–83. https://doi.org/10.5736/jares.31.3_79