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Japanese Wild Boars Head North: Snow Depth Decrease, Wildlife Conflict, and Structural Changes in Agriculture

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Abstract

Human–wildlife conflicts, specifically the damage caused to crops and livestock, pose a significant challenge that affects agriculture. Climate change has exacerbated this issue by altering the distribution and behavior of wildlife. This study examines how farmers respond to the increasing encroachment of Japanese wild boars on farmlands, using panel data at the farm level. The study exploits the expansion of wild boar habitats owing to reduced snow depth. The results show that the presence of wild boars leads to farm exits. In addition, we observe a negative effect on farm size. These effects are driven by an increase in abandoned farmland and a decrease in rented-in farmland. The findings suggest that human–wildlife conflicts hinder structural changes in agriculture.

Keywords: Farm Exit, Farm Size, Human–wildlife conflicts, Climate change

JEL: Q18, Q24, Q57.

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1. Introduction

Human–wildlife conflict is a challenging issue that poses significant obstacles to agriculture worldwide. Specifically, the direct damage caused by wildlife to crops and livestock is a considerable economic cost that affects agricultural production and sustainability (Woodroffe, Thirgood, and Rabinowitz 2005). There are also indirect costs associated with the destruction of agricultural machinery, protection measures such as hunting and fencing, and crop changes. Furthermore, climate change has worsened the cost of human–wildlife conflict (Abrahms 2021; Abrahms et al. 2023). Changes in temperature and precipitation patterns have led to changes in vegetation cover and food availability for wildlife, causing them to move to new areas, including agricultural regions. This movement, in turn, increases the risk of human–wildlife conflicts, resulting in further economic losses for farmers. Understanding the potentially disruptive effects of wildlife conflict to ensure agricultural sustainability is critical.

A growing body of literature has explored the costs of wildlife conflict, particularly with ungulates such as wild boars and deer (Chardonnet et al. 2002; Rao et al. 2002; Schley and Roper 2003; Geisser and Heinz-Ulrich 2004; Schley et al. 2008; Pandey, Shaner, and Sharma 2016; Podgórski and Śmietanka 2018; Gren et al. 2020; McKee, Shwiff, and Anderson 2021) as well as carnivores to farming (Muhly and Musiani 2009; Sommers et al. 2010; Ramler et al. 2014; Widman and Elofsson 2018; Mink, Loginova, and Mann 2023). However, little is known about how farmers respond to climate-change-induced wildlife conflicts, particularly whether to reduce production or leave farming completely. Our study analyzes wildlife conflicts in northern Japan—a plausibly exogenous climate change that gradually causes wildlife conflicts—and its consequences for subsequent structural changes in agriculture. Insight into the potential relationship between wildlife behavioral changes and agriculture is essential for ensuring long-term agricultural sustainability.

This study examines how farmers respond to wildlife conflicts, specifically focusing on Japanese wild boars (*Sus scrofa leucomystax*). It makes two significant contributions. First, it explores the impacts of wildlife on farm exits, which has been neglected in the literature. Second, it documents the productive responses of surviving farmers, mainly the changes in farmland use. This reallocation of labor from agriculture to other sectors and changes in farm size represent adjustments in farm structure, which are core components of broader agricultural structural change (Deininger, Jin, and Ma 2022). In this study, "structural change" is defined as farm exit, size adjustment, and land consolidation—key components of agricultural transformation in developed economies (Chavas 2001; Eastwood, Lipton, and Newell 2010)—although we recognize that the term can encompass a broader range of economic and institutional changes (Chavas 2001). To the best of our knowledge, this study is the first to document the impacts of wildlife on these structural adjustments (e.g., changing the number of farms and hindering the growth in average farm size through consolidation). This has significant implications for quantifying wildlife damage and understanding their potential effects on agricultural structural adjustment.

We focus on wild boars, which are among the most widely distributed large mammals in all continents except Antarctica (Massei et al. 2015). The global population of wild boars has increased in numerous countries worldwide (Schley et al. 2008; Massei et al. 2015; Pandey, Shaner, and Sharma 2016). Wild boars are considered one of the most harmful species responsible for crop damage (Linkie et al. 2007; Schley et al. 2008; Barrios-Garcia and Ballari 2012; Pandey, Shaner, and Sharma 2016). The emergence of wild boars presents a policy-linked issue, as it has progressively led to conflicts with farming.

Empirically identifying the causal effects of the emergence of wild boars presents challenges. While the emergence of wild boars may impact the behavior of farmers in various ways, the behavior of farmers may also affect the wild boars (Nyhus 2016), and unobserved factors may influence both. For instance, if the emergence of wild boars partly reflects geoclimatic features, and this attribute changes farmland use, our estimates of the impact of wild boars may be biased. Furthermore, farmland use change, such as an increase in abandoned farmland, may affect the emergence of wild boars because it provides a suitable habitat for them (Sieber et al. 2015).

To identify the causal link between wild boars and structural changes in agriculture, we propose an identification strategy that exploits the expansion of wild boar habitats resulting from climate change. Snow depth is one of the main factors that heavily influence the habitat of wild boars (Lemel, Truvé, and Söderberg 2003; Melis et al. 2006; Rosvold and Andersen 2008; Gren et al. 2018). Ecological evidence shows that Japanese wild boars have difficulty inhabiting areas with over 30 cm of snow cover owing to their short legs relative to their body mass (Asahi, Hitomi, and Yamamoto 1972; Tsuneda and Maruyama 1980; Shimizu, Mochizuki, and Yamamoto 2013). Another study shows that reductions in snow depth caused by climate change have expanded the range of Japanese wild boars (Saito et al. 2016). Climatic factors like temperature and precipitation generally determine agricultural land use and crop selection. However, snow depth does not affect farming from spring to fall, as no cultivation occurs in the study area during winter owing to snowfall. Thus, as an instrumental variable (IV), climate-change-induced snow depth correlates only with farm exit and farmland use through the distribution of wild boars.

Our study focused on Japanese farm households in snowy areas, specifically the Tohoku and Hokuriku regions. During the survey period (2000–2015), wild boars were observed in these regions because of the rapid expansion of their habitat distribution in response to climate change. We constructed an IV for the distribution of wild boars using meteorological data at the grid cell level of 1×1 km cells from Japan's National Agriculture and Food Research Organization (NARO). We calculated the average number of days during winter (November–March) over the last 5 years when the snow depth did not exceed 30 cm before the year when the wild boar distribution was surveyed. To examine the impact of wild boar emergence on farming households, our empirical analysis combined this information with Japanese farming household data for 2000, 2005, 2010, and 2015 and data on the distribution of wild boar habitats for 2003, 2011, and 2014 at the grid cell level of 5×5 km cells from the Population Estimation and Habitat Distribution Survey of Japanese deer and wild boars (Ministry of the Environment 2020).

Our main results show that farm households in areas where wild boars are present are more likely to leave their farms. Specifically, the preferred specification indicates a 14.4-percentage point decrease in the likelihood of continuing farming 5 years after the emergence of wild boars in the sample. This effect is economically significant, given that farm households have decreased by an average of 20.1% every 5 years. We also find suggestive evidence of a decrease in farm size, as measured by operated farmland, in areas affected by wild boars compared with those without. These effects are driven by increased abandoned farmland and a decreased rented-in farmland. Regarding the heterogeneity of the results, the emergence of wild boars impacted part-time farm households but had little impact on full-time farm households. The farmland of part-time farm households who have either left farming or reduced their farm size has not been consolidated with the remaining full-time farm households, potentially because full-time farm households have less incentive to utilize these specific plots due to lower productivity or higher prevention costs associated with land affected by wild boars. The findings imply that wildlife conflict hinders structural changes in agriculture.

Our study contributes to the existing literature examining wildlife's economic impact (Gren et al. 2018; Widman and Elofsson 2018; Mink, Loginova, and Mann 2023) by offering novel insights into farmers' responses to wildlife. Our research highlights the significant impact of wildlife conflicts on structural changes in agriculture. By focusing on indirect costs, compared with previous studies that primarily focused on the direct costs of wildlife conflict (e.g., crop loss and predation), we provide a new perspective on the impact of wildlife conflicts and their role in hindering agricultural structural change.

Our results are relevant to the literature on the effects of climate change on agriculture. Previous studies have examined the direct effects of climate change on crop yield (Burke and Emerick 2016), agricultural productivity (Njuki, Bravo-Ureta, and Cabrera 2020; Ortiz-Bobea et al. 2021), agricultural labor (Colmer 2021), farmland use (Aragón, Oteiza, and Rud 2021), and production quality (Kawasaki and Uchida 2016). Our research examines the indirect impact of climate change on agriculture through changes in wildlife distribution. This study highlights the importance of snow depth apart from temperature and precipitation, owing to its sensitivity to global warming. Additionally, it illuminates the complex interactions between climate change, wildlife, and agriculture by emphasizing their indirect effects.

This study also contributes to the literature on structural change in agriculture. Previous studies have examined the impacts of agricultural productivity (Bustos, Caprettini, and Ponticelli 2016), agricultural diversity (Fiszbein 2022), agricultural production patterns (Engerman and Sokoloff 2002), and climate change (Albert, Bustos, and Ponticelli 2021). In this study, we explored an underexamined area: the indirect effects of climate change on agricultural structural change through wildlife conflicts. Our study provides empirical evidence supporting anecdotal reports suggesting that wildlife conflict leads to crop damage, forced farm closures, and an increase in abandoned lands. The emergence of wildlife conflict may be a significant obstacle to the progress of agricultural structural change. Our findings will aid policymakers and development practitioners seeking to promote agricultural transformation in areas where wildlife conflicts pose a significant threat to farmers' livelihoods, particularly by hindering land consolidation.

The remainder of this study is organized as follows. Section 2 provides the background and contextual framework. Section 3 presents the dataset and describes the construction of the snow depth variables. Section 4 explains the empirical strategy. Section 5 presents the estimation results. Finally, Section 6 concludes the study.

2. Background

Farming in Japan

Our empirical analysis focuses on farm households in Japan. Like other advanced economies, Japan has experienced a persistent decline in the number of people employed in agriculture (Ramsey, Ghosh, and Sonoda 2019; Ramsey, Sonoda, and Ko 2023). In 2019, the agricultural sector employed only 3.1% of the workforce and contributed only 0.9% to the gross domestic product (GDP). The data show that agricultural labor productivity is relatively low and exhibits characteristics similar to those of developing countries, primarily comprising small-scale productive units (i.e., households). Although the average operated farmland area per household has increased from 1.4 hectares in 1990 to 3.1 hectares in 2020, it remains small compared with OECD countries. The prevalence of part-time farm households contributes to low agricultural productivity. In 2022, around 730,000 farm households, accounting for roughly 78% of the 935,000 farm households, earned over 50% of their income from non-agricultural sources, such as non-farm employment and retirement income.

The average age of farmers in 2020 was 67.8, with 70% over 65. This contrasts with the situation in many OECD countries. However, like other advanced economies, the agricultural structure in Japan exhibits high polarization: while a substantial number of small-scale farm households, the top 3% of large-scale farm households, cultivate over half of the total farmland area (Organisation for Economic Co-operation and Development 2019). Encouraging the concentration and intensification of farmland among large-scale farmers is crucial to promoting efficient agriculture in the future.

Wild Boar Habitat Expansion

The Ministry of the Environment (MoE) has published nationwide distributions of wild boars in 1978, 2003, 2011, 2014, and 2020, accompanied by habitat distribution maps at the 5 km mesh level (Figure 1). The initial nationwide survey in 1978 confirmed wild boar distribution in 5,188 of 17,376 meshes nationwide, constituting approximately 30% of the total meshes. Wild boars are predominantly observed in southwestern Japan, as they avoid colder regions in the north owing to their inability to hibernate. Since the early 2000s, their population has increased, resulting in their natural expansion into new areas (Ministry of the Environment 2020). According to the 2020 survey, wild boars are distributed in 9,641 meshes, representing approximately 60% of the nationwide meshes. Over the past 40 years (1978–2020), the distribution area of wild boars has expanded by approximately 1.9 times. Wild boars now inhabit snow-covered regions of northern Japan, especially Tohoku and Hokuriku, which were previously considered unsuitable for survival.

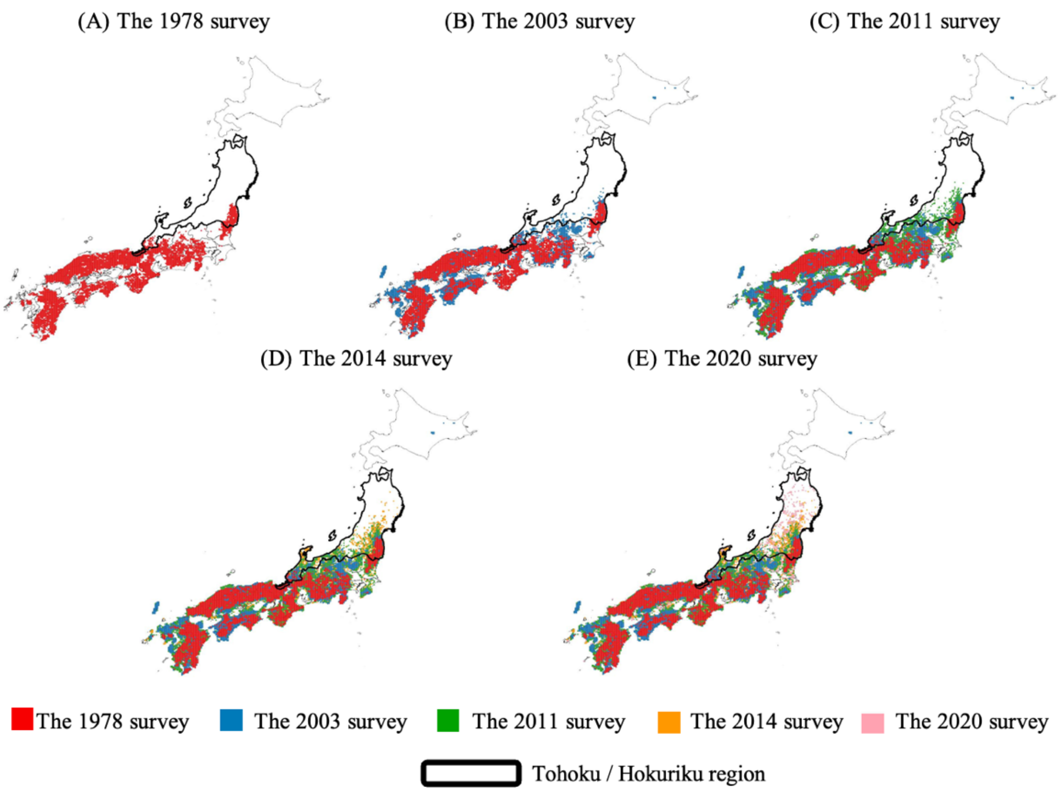

Figure 1 The distribution of Japanese wild boars

Sources: Ministry of the Environment (2020).

Note: The dots represent wild boars observed between the 1978 and 2020 surveys. The black lines represent Tohoku and Hokuriku regions.

Wild Boar Conflicts

Because of the expansion of wild boar habitats, crop damage, particularly to rice, fruit, and vegetables, has become increasingly significant in recent years. This damage is caused by crop consumption and trampling during foraging. In 2021, wild boars caused 3.9 billion JPY in crop damage, accounting for approximately 25% of the total agricultural loss of 15.5 billion JPY caused by wild animals (Ministry of Agriculture, Forestry and Fisheries 2022). Excluding the Hokkaido region, where wild boars are not naturally distributed, wild boars caused approximately 38% of the total loss of 10.2 billion JPY. Although the overall amount of crop damage caused by wild boars has shown a downward trend since 2013, the damage per unit of operated farmland has increased owing to the decreased availability of farmland. In 2021, the damage per unit of operated farmland reached approximately 40,000 JPY/ha.

However, the costs associated with wild boars go beyond the direct damage and include the cost of machinery damage due to wild boar nesting; reduced silage and grain quality due to soil contamination; and mitigation measures, such as agricultural fencing and avoiding the cultivation of crops favored by wild boars (Gren et al. 2018).

Furthermore, farmers often need to make additional efforts to protect their crops from wild boars. Once wild boars invade the farmland, they exacerbate the existing damage within the farmland. This means farmers implement costly measures and invest time to mitigate the damage. For example, fencing with electric, wire mesh, and net fences is often installed to prevent the intrusion of wild boars into communities and fields. To maximize the fence's effectiveness, it is essential to maintain them properly after installation. This includes daily voltage checks, regular patrols, and periodic mowing of the electric fences to prevent electrical leakage. The electric fences must be removed and reinstalled after snow melts in winter. Moreover, mowing weeds from the area around the fences also reduces the likelihood of wild boars' intrusion, minimizing the risk of fence destruction and breaches. Kuwabara and Kato (2012) estimated the prevention costs to be around 40,000 JPY per ha in the first year and maintenance costs to be around 5,000 JPY per ha annually.

These accumulated direct and indirect costs, including the significant labor burden for maintenance and vigilance, can become prohibitive, particularly for smaller, marginal, or older-adult/part-time farm households. Moreover, wildlife damage is often highly concentrated geographically (e.g., in mountainous areas or near forests), meaning that national or regional average damage figures mask the severe economic pressure faced by specific communities and individual farmers, potentially acting as a "tipping point" for their exit decisions.

Consequently, considering the substantial indirect costs and prevention efforts detailed above alongside the direct crop damage, the total economic burden associated with wild boar presence appears significantly higher than official damage statistics alone reflect. Hence, the impact of wild boar habitat expansion on agricultural viability can be more profound than initially perceived solely based on monetary damage. Direct climate change impacts, like temperature increases, are recognized as significant drivers of agricultural outcomes. Kawasaki and Uchida (2016), for example, estimate a 4.6% farm revenue decrease from a 3°C warming in Japan (equating to roughly 64,000 JPY/ha based on 2021 figures). However, the combined direct and extensive indirect costs imposed by the expansion of wild boars under climate change could represent a comparable or even larger financial pressure on affected farm households. This underscores the importance of accurately estimating the full impact of climate change-induced wildlife conflicts, like the wild boar expansion examined in this study, for understanding farmer decision-making and developing effective adaptation strategies.

While substantial efforts have been undertaken by both farmers and the government to prevent damage, persistent structural and ecological challenges constrain the overall effectiveness of these measures. The Japanese government implements such schemes as the Comprehensive Countermeasures Grant for Wildlife Damage Prevention, which supports municipal initiatives through subsidies for protective fencing and capture equipment. Many local municipalities also offer supplementary schemes. However, the efficacy of these measures faces several hurdles. First, fences require ongoing monitoring and maintenance against intelligent wildlife, including boars, which learn to exploit weaknesses. Second, this essential maintenance is becoming increasingly difficult because of the declining number and aging of farmers in many rural areas. These complexities highlight the ongoing difficulty in managing human–wildlife conflict despite existing policy efforts.

Structural Changes in Agriculture Induced by Wild Boars

The emergence of wild boars can trigger structural changes in agriculture. Direct crop damage and the increased workload imposed by wild boars (i.e., indirect damage) may lead to a decline in farmers' willingness to engage in farming and an increase in abandoned farmland. Indeed, increasing farmer exits does not necessarily imply a simple reduction in overall farmland. The total farmland area, for instance, remains unchanged if other farmers overtake the farmland; on the contrary, those acquiring the farmland may expand their total operated farmland area. However, farmland previously abandoned by farmers due to encounters with wild boars incurs additional costs for preventing the intrusion of wild boars and managing damage. In such cases, no farmers may take over the farmland. This situation hinders the expansion of farm size by the remaining farmers. The emergence of wild boars may prompt farmers to exit and hinder the overall agricultural structure change.

3. Data

Unit of Observation and Sample

This study examines the impact of wild boar exposure on agricultural structural changes. We apply multiple data sources (Table A.1). Our dataset combines household surveys with wild boars and weather variables to create a comprehensive dataset. Our unit of observation is a farm household in a given census year (specifically 2000, 2005, 2010, and 2015), and the sample is limited to farm households engaged in agricultural activities (excluding subsistence farm households) in the Tohoku and Hokuriku regions. The final dataset comprises approximately 1,535,307 observations every 5 years from 2000 to 2015.

Data Sources

The first dataset provides information on the distribution of wild boar habitats in Japan. These data were obtained from the Population Estimation and Habitat Distribution Survey of Japanese deer and wild boars by the MoE. The MoE has published survey results for wild boar distribution in 1979, 2003, 2011, 2014, and 2020. The surveys conducted to gather information on wild boar distribution include interviews, field surveys, and questionnaires administered to forest managers, forest researchers, park rangers, hunters, and forest owner cooperatives (Saito et al. 2016). New distribution areas are recorded based on wild boar sightings (both live and dead) reported by respondents in 3’45”×2’30” grid cells (approximately 5×5 km², hereafter referred to as “5-km grid cells”). We utilize information from the 2003, 2011, and 2014 surveys to maintain consistency with other data. The 2003, 2011, and 2014 surveys cover the habitat distribution from 2000 to 2002, 2007 to 2009, and 2012 to 2013, respectively (Table A.2). Figure 1 illustrates the distribution of wild boars in Japan in 5-km grid cells. The wild boar habitats have expanded northward since 2003.

The second dataset includes snow data from the Agro-Meteorological Grid Square Data (AMGSD) of the NARO, Japan. The AMGSD provides daily meteorological weather data across 14 types of 1-km grid cells for the entire country. These data, from January 1, 1980 (or partial data for some elements from January 1, 2008) to the day before, are created based on meteorological observations conducted at approximately 1,300 points (Ohno and Sasaki 2019). We use snow cover duration and snow depth during the winter season as climatic variables to explain the distribution of wild boars. The winter season is defined as November–March. The weather data cover the period from 2000 to 2015, aligning with the wild boar distribution data period. We calculated the average number of days when snow depth did not exceed 30 cm during winter (November–March) in the last 5 years since the year the wild boar distribution was surveyed.

The third dataset includes information on the farming activities of commercial farm households. These farm households are defined as those with more than 0.3 hectares of operating farmland or more than 500,000 JPY in agricultural product sales. The data are obtained from the Census of Agriculture and Forestry conducted by the MAFF. The census has been conducted every 5 years since 1950 and provides a measure of the current agricultural conditions in Japan. The provided data includes information on farmland and labor resources at the farm household level. The data are available for 2000, 2005, 2010, and 2015.

Our empirical analysis combines data on Japanese farming households from 2000, 2005, 2010, and 2015 with data on the distribution of wild boar habitats. The location of farmers' residences is identified at the rural community level, representing the smallest unit of regional society within the municipality. Using a community-level shapefile, we identify all communities where farm households are located. To link the wild boar distribution and farm household data, we match each farm household with the wild boar distribution in the grid cell that overlaps with the central coordinates of the community where the farm household resides. We aggregated the weather data up to the level of community. Our baseline specification focuses on the exposure to wild boars during the periods covered by farm household data.

Our study focuses on the Tohoku and Hokuriku regions for four reasons (Figure 1). First, these regions in northern Japan have experienced a decline in snow cover during winter, leading to the expansion of wild boar habitats. Second, these regions receive significant snowfall in winter, which is essential for investigating the relationship between snow cover and wild boar distribution. Third, winter crop cultivation has not been practiced traditionally in this region owing to cold and snowy winters, despite decreasing snow cover in recent years. Finally, by focusing on a specific region in Japan, we mitigate the potential confounding factors that arise in cross-regional settings, including institutional and cultural norms within rural communities.

Indicators of Structural Changes in Agriculture

We examine two outcomes as indicators of structural changes in agriculture: farm exits and farm size. The agricultural sector has undergone significant structural changes, manifested by a declining number of farms and farm size expansion during development (Eastwood, Lipton, and Newell 2010; Lowder, Skoet, and Raney 2016). Farm exits are recognized as crucial drivers of structural changes in agriculture. Our primary focus is farm exits, defined as "exiter" and "stayer" in Table 1. An exiter is classified as a farm household present in 2000 but absent in the subsequent year, indicating that they left the commercial farm household. By contrast, a stayer is a farm household that remains present in all surveyed years, indicating continuous engagement in commercial farming. It is unclear whether households absent in the following year ceased farming or transitioned to subsistence farming. Likewise, if a farm household is absent in one year but reappears in the next, it is unclear whether they are new to farming or have shifted from subsistence to commercial farming. To address this issue, we limit our sample to commercial farm households from the 2000 dataset, considering only those that either exit the sample or remain present in subsequent years. This allows us to apply our farm exit indicator to measure the households that quit commercial farming. Table 2 summarizes the exit patterns of the samples. Approximately 18% of farm households exited within the first 5 years. After 10 years, approximately 65% of farm households were still engaged in farming, and after 15 years, 51% remained, resulting in an average exit rate of approximately 20.1% per 5 years between 2000 and 2015. The declining trend of farm households in the Tohoku and Hokuriku regions shows the same trend as that of farm households at the national level (Table A.3).

Table 1 Definition of farm household exit at different times

	2000	2005	2010	2015
Exiter	Observed	Not observed	Not observed	Not observed
Exiter	Observed	Observed	Not observed	Not observed
Exiter	Observed	Observed	Observed	Not observed
Stayer	Observed	Observed	Observed	Observed

Table 2 Number of farm households as well as stayers and exiters farm households

Year	Farm households	Stayers		Exiters	
	N	N	%	N	%
2000	515,492	421,190	81.7%	94,302	18.3%
2005	421,190	335,945	79.8%	85,245	20.2%
2010	335,945	262,680	78.2%	73,265	21.8%
2015	262,680				

Our second focus is on farm size. We measured the farm size based on the amount of operated farmland. Operated farmland is a widely used indicator of farm size because it reflects the availability of farmland, a factor that often constrains farm development (Bartolini and Viaggi 2013). Table 3 summarizes the descriptive statistics of the variables (excluding farm exits) used in our analysis. Operated farm size increased by approximately 10% per census year (every 5 years), which has increased by 35% over the 15-year study period. The change in farm size over time follows the same trend as the change in farm size at the national level (Table A.4).

Table 3 Descriptive statistics by census year

	2000	2005	2010	2015
Outcome				
Operated farmland (ha)	1.58	1.73	1.92	2.16
Rented-in farmland (ha)	0.23	0.32	0.44	0.59
Share of rented-in farmland	5.71	6.36	7.44	8.26
Abandoned farmland (ha)	0.06	0.07	0.08	0.11
Share of abandoned farmland	4.66	5.10	5.42	7.06
Treatment				
Wild boar presence dummy (1 if yes)		0.08	0.23	0.35
Instrumental Variables				
Average number of days with less than 30 cm of snow depth for past 5years in winter		109.17	110.44	102.28
Controls				
Age	57.85	60.38	62.98	65.95
Male farm household head dummy (1 if yes)	0.95	0.96	0.96	0.96
HH member	4.71	4.55	4.28	3.98
Full-time farm household dummy with farm workers under 65 years old (1 if yes)	0.04	0.05	0.08	0.09
Family farming dummy (1 if yes)	1.00	1.00	1.00	1.00
Ratio of paddy area	82.97	83.69	80.94	80.66
Average temperature for past 5years in growing seasons		18.0	17.7	17.9
Average temperature for past 5years in non-growing seasons		2.7	2.8	2.4
Average precipitation for past 5years in growing seasons		5.0	4.8	4.6
Average precipitation for past 5years in non-growing seasons		4.6	4.7	4.9
Average GDD for past 5years		1780.1	1794.0	1778.5
Sample size	515,492	421,190	335,945	262,680

4. Empirical Framework

The presence of wild boars and farm exit (or farm size) may be influenced by omitted variables that affect both. The emergence of wild boars may reflect unsuitable agricultural conditions that negatively affect farm exit (or farmland use). For example, it can introduce bias if the controls do not adequately capture market access. While the controls in the ordinary least squares estimations aim to account for some of these factors (e.g., crop rotation, unsuitability of the area for agriculture, and market access), adding additional controls might not fully capture these effects. Additionally, other unobservable factors may cause omitted variable bias. To identify causal effects, this section introduces an IV strategy that leverages exogenous variation in the distribution of wild boar habitats driven by climatic features. We begin by describing the construction of an IV for the distribution of wild boar habitats.

Empirical Strategy

To examine the impact of wild boars on farm exit and farm size, we employ an IV approach to address the potential nonrandom distribution of wild boar habitats. This identification strategy relies on the fundamental insight that climatic features partly affect the distribution of wildlife habitats. In general, the behavior of wild boars is significantly affected by snow cover that exceeds the height of their hind limb appendages (Gilbert, Wallmo, and Gill 1970). Wild boars have shorter legs relative to their body weight than other large mammals, making it challenging to be active in deep snow. Additionally, deeper snow cover makes it more difficult for wild boars to access food by digging (Chiyojima et al. 2022). Indeed, the coastal areas along the Sea of Japan (i.e., north of the Chubu region in Japan) serve as the northern boundary for the worldwide distribution of wild boars owing to substantial snow accumulations during winter.

Similarly, ecological evidence shows that a relationship between the duration of sustained snow depth of approximately 30 cm and the absence of wild boar distribution has been observed (Asahi, Hitomi, and Yamamoto 1972; Tsuneda and Maruyama 1980). Japanese wild boars experience periods of expansion and contraction in their distribution range along snow conditions (Tsujino, Ishimaru, and Yumoto 2010). For example, heavy snowfall during the Edo period (16th century to the mid-19th century), known globally as the "Little Ice Age," may have contributed to the extinction of wild boars in areas with heavy snowfall along the Sea of Japan (Matsui and Ogawa 1987). Thus, the absence of wild boars in areas with heavy snowfall, such as the Tohoku and Hokuriku regions, is primarily attributed to snow cover, a natural limiting factor in their distribution. The recent trend of decreasing snowfall, reflected in an increased number of days with snow depth not exceeding 30 cm (Figure 2), has expanded the habitat range of this species. Consequently, wild boars are now found in northern Japan, as illustrated by their expanded distribution (Figure 1). According to Kodera et al. (2001), the increase in agricultural damage caused by wild boars is attributed to decreased snow cover caused by global warming.

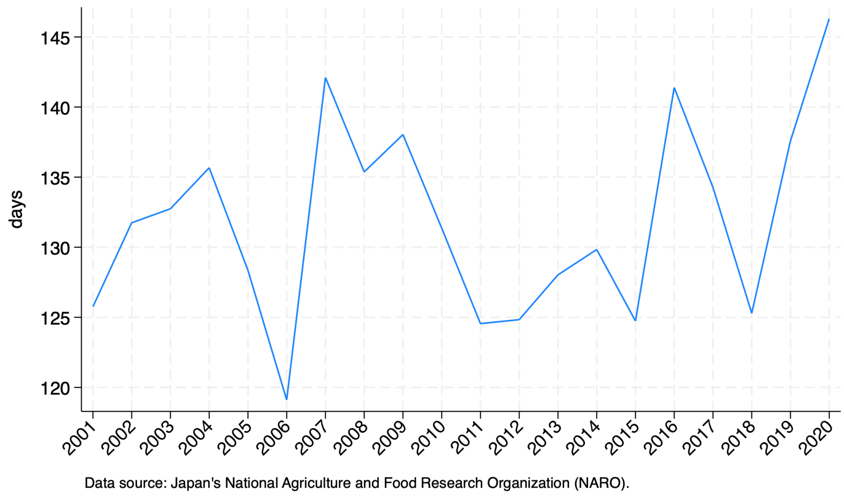

Figure 2 The average number of days when snow depth did not exceed 30 cm during winter (November–March) in the study area

Snow depth is utilized as an instrument variable for the emergence of wild boars in Japan's Tohoku and Hokuriku regions. Based on the ecological evidence (Asahi, Hitomi, and Yamamoto 1972; Tsuneda and Maruyama 1980), we use the average number of days with snow depth below 30 cm during winter (November–March) in the last 5 years when the wild boar distribution was surveyed. Generally, climatic factors, such as temperature and precipitation, affect farmland and farm exits (Burke and Emerick 2016; Aragón, Oteiza, and Rud 2021). However, farming in winter is not practiced in the Tohoku and Hokuriku regions of the study area owing to winter snowfall. Therefore, the average number of days when the snow depth did not exceed 30 cm during winter in the last 5 years since the year the wild boar distribution was surveyed (i.e., our IV) does not directly affect our outcomes. This indicates that changes in snow depth due to climate change only correlate with farm exits and farmland use through the distribution of wild boars.

Specification

Given the potential endogeneity, we consider a plausibly exogenous source of variation in wild boar distribution. Identification is based on variations in snow depth (less than 30 cm) and snow cover duration over time and across different regions. Weather patterns vary significantly in a context-specific manner, even among neighboring communities. In other words, conditional on the fixed effects, we assume that changes in snow depth and snow cover duration are random and do not directly affect our measures of agricultural structure. We further assume that any correlation between these snow variables and agricultural structure operates solely through their impact on wild boar emergence. Our IV estimation relies on the following first-stage equation:

$$Wild\ boar_{i,c,t} = \alpha_1 Snow_{i,c,t} + \alpha_2 X_{i,c,t} + \mu_i + \lambda_t + \epsilon_{i,c,t}, \ (1)$$

where $Wild\ boar_{i,c,t}$ is the emergence of wild boars in community c in year t where farm household i is located; $Snow_{i,c,t}$ is the average number of days in which the snow depth does not exceed 30 cm during winter (November–March) in the last 5 years, since the year when the wild boar distribution was surveyed in community c in year t where farm household i is located; $X_{i,c,t}$ is a set of farm household level controls; μ_i and λ_t indicate farm household and year fixed effects, respectively; $\epsilon_{i,c,t}$ is a random term.

Our second stage for the effect on farm exit is given by

$$Farm\ survival_{i,c,t+1} = \beta_1 \widehat{Wild\ boar}_{i,c,t} + \beta_2 X_{i,c,t} + \mu_i + \lambda_t + \nu_{i,c,t}, \ (2)$$

where $Farm\ survival_{i,c,t+1}$ is a dummy for whether farm household i in community c in year t is present or absent in year t+1; $\nu_{i,c,t}$ is a random term, and the other variables are the same as those defined in the first stage.

Next, our second stage for the effect on farmland use is given by

$$Ln\ (Farm\ size_{i,c,t}) = \gamma_1 \widehat{Wild\ boar}_{i,c,t} + \gamma_2 X_{i,c,t} + \mu_i + \lambda_t + \upsilon_{i,c,t}, \ (3)$$

where $Farm\ size_{i,c,t}$ is operated farmland for farm household i in community c in year t; $\upsilon_{i,c,t}$ is a random term, and the other variables are the same as those defined in the first stage.

The controls used in the above regressions include farm household characteristics (household head's age, male farm household head dummy, number of household members, full-time farm household dummy, family farming dummy, and ratio of paddy area). Our goal is to control for farm household characteristics that may directly affect farm exit decisions and farmland use. Conditional on these farm household characteristics, we assume that the instrumented wild boar habitat distribution should not have other indirect impacts on farm exit decisions and farmland use. In addition, the interaction between the prefecture and time fixed effects is included to consider countermeasures against the damage caused by wild boars in each prefecture.

We also include the temperature and precipitation variables based on the average temperature or precipitation for each growing and non-growing season in the last 5 years since the year the wild boar distribution was surveyed. That addresses concerns that our IV (snow depth and coverage changes) might not directly affect the agricultural structure but rather be correlated with it through weather changes. For example, less snow depth may be associated with higher temperatures. These cases could lead to upwardbiased estimates concerning wild boar distribution and snow depth. Weather patterns are region-specific and vary widely even among neighboring communities. Nevertheless, the differences in daily temperature distribution may still cause some of these concerns.

Therefore, as additional robustness checks to potential variability in weather impacts, we performed IV estimation by incorporating temperature and precipitation bin variables for each growing and non-growing season. The temperature bins were set in 5°C increments from 0–35°C, with the final bin including temperatures above 35°C. For precipitation, bins were set in 2 mm increments (e.g., 0–2 mm, 2–4 mm, and so on, with a final bin for values above 10 mm). We used variables for the average number of days within each bin over the past 5 years.

We also included growing degree days (GDD) as a weather variable, calculated by summing temperature exposures within a base temperature of 10°C and an upper threshold of 30°C, where temperatures above 30°C contribute to 20-degree days. The average GDD over the past 5 years was used. These checks allay concerns about violating the exclusion restriction in the IV estimation due to spurious correlations.

5. Results

Main Results

Table 4 presents the IV estimation results for the outcomes of structural changes in agriculture: farm exit and farm size. Columns (1) of Panel A and B show the results with individual and time fixed effects, control variables, temperature and precipitation variables, temperature and precipitation squared variables, and the interaction between prefecture and time fixed effects. The results in Column (2) include the growing season and non-growing season temperature and precipitation bin variables, while columns (3) and (4) include the GDD variables. In all specifications, the IV estimates show the significant negative effects of wild boars on the outcomes. The first stage results highlight the strength of snow depth as an instrument, with both F-statistics exceeding 67.98 in Column (1) of Panel A and 75.58 in Panel B. Although there is an increase in the magnitude of the coefficient from the first to the second column, a consistent negative effect of wild boars on farm survival and farm size is observed.

Table 4 The effect of wild boars on farm Survival and farm size (IV estimates)

	(1)	(2)	(3)	(4)
Panel A. Outcome: Farm survival				
Second-stage				
Wild boar	-0.144 **	-0.227 **	-0.319 ***	-0.314 ***
	(0.065)	(0.088)	(0.115)	(0.108)
First-stage				
Number of days with less than 30 cm of snow depth	0.002 ***	0.002 ***	0.001 ***	0.001 ***
	(0.000)	(0.000)	(0.000)	(0.000)
F (first stage)	67.98	40.91		32.08
Observations	1,272,627	1,272,627	1,272,627	1,272,627
Panel B. Outcome: Ln (Operated farmland)				
Second-stage				
Wild boar	-0.122 **	-0.175 ***	-0.197 **	-0.178 **
	(0.050)	(0.064)	(0.078)	(0.071)
First-stage				
Number of days with less than 30 cm of snow depth	0.002 ***	0.002 ***	0.001 ***	0.002 ***
	(0.000)	(0.000)	(0.000)	(0.000)
F (first stage)	75.58	51.55	27.82	41.56
Observations	1,019,815	1,019,815	1,019,815	1,019,815
Mean temperature in growing seasons and non-growing seasons	Yes			
Mean temperature squared in growing seasons and non-growing seasons	Yes			
Mean precipitation in growing seasons and non-growing seasons	Yes		Yes	
Mean precipitation squared in growing seasons and non-growing seasons	Yes		Yes	
Temperature bin in growing seasons and non-growing seasons		Yes		
Precipitation bin in growing seasons and non-growing seasons		Yes		Yes
GDD			Yes	Yes
Controls	Yes	Yes	Yes	Yes
Farm household FE	Yes	Yes	Yes	Yes
Prefecture * Year FE	Yes	Yes	Yes	Yes

Observations are farm households-year. SEs clustered at the farm household level and communituy level are in parentheses. Farm survival is a dummy. Wild boar presence variables are dummies at the community level. *** $p < 0.01$, and ** $p < 0.05$.

The emergence of wild boars has a detrimental impact on farming persistence, which is consistent with our expectations. Column (1) of Panel A indicates that farm households in areas where wild boars have appeared are 14.4 percentage points less likely to continue farming after 5 years. These effect sizes are substantial, considering that 20.1% of farm households exit after 5 years as is shown in Table 2. Therefore, we can conclude that farm households are sensitive to the emergence of wild boars. Our results are consistent with those of Mink, Loginova, and Mann (2023), who argued that the number of wolf attacks affects changes in the number of alpine summer farms. Our findings imply that the emergence of wild boars impels farmers to leave farming because of the increased overall burden, including crop damage and prevention costs.

Given the results of a significant effect of wild boars on farm exits, we could focus on the structural change in agriculture as a redistribution of the remaining farmland between exiting and surviving farm households. Columns (1) of panel B in Table 4 also demonstrate the effect of wild boars on farm size. The results reveal a 12.2% decrease in farm size in communities where wild boars emerge. Surviving farm households in communities with wild boars are more likely to decrease their farm size. This implies the slowdown of structural changes in agriculture, especially farm size expansion. Given the additional costs associated with fencing and other preventive measures against new boar incursions, it is reasonable for surviving farmers to expect the negative impact of wild boars on farmland size.

Identification and Robustness Checks

To further establish the credibility of our main findings regarding the impact of wild boars on farm exits and farmland use, we conducted several additional exercises. We first examine the sensitivity of our results to alternative definitions of our instrumental variable (snow depth). We then address potential sample selection bias using the Heckman two-step procedure and conduct additional checks related to sample definition and aggregation level. Finally, we demonstrate the robustness of our findings using an alternative estimation strategy (a long-difference model).

Alternative Measures of IV—We examined the sensitivity of our results to various definitions of IV used to measure snow depth. We explored alternative IV measures to address potential measurement issues. First, Table A.5 considers IV capturing the distribution of snow depth days. Instead of using just the average number of days during the winter (November–March) when snow depth did not exceed 30 cm, we created snow depth bins to capture snow depth distribution. Specifically, we defined the snow depth bins with cutoffs at intervals of 10 cm (0–10 cm, 10–20 cm, 20–30 cm, and above 30 cm) and calculated the average number of days within each bin over the past 5 years. Table A5 of the online appendix shows that the estimated results remain robust when these snow depth bin variables were used as the IV. Second, Table A.6 shows similar estimates of the effects of wild boars on farm survival and farm size obtained from a different timeframe IV created from 7-year snow depth measurements.

Addressing Potential Sample Selection Bias—A potential concern when estimating the effect of wild boar presence on farm size (operated farmland) is sample selection bias, as the analysis focuses on farms that continued operating, potentially overlooking systematic differences related to the exit decision. Failure to account for this could bias our estimates if unobserved factors influencing the exit decision are also correlated with farm size among survivors.

To address this important issue, we implemented the Heckman two-step procedure, following the specific methodology outlined in Wooldridge (2010) for handling sample selection with an endogenous explanatory variable. First, we estimated a probit model for the farm survival decision to calculate the Inverse Mills Ratio (IMR). The presence of a successor was used as the exclusion restriction for identification. The rationale is that the presence of a successor is expected to strongly influence the household's decision to continue farming, as it provides an incentive for intergenerational transfer of the farm. However, conditional on the decision to continue farming and other farm household characteristics, the mere presence of a successor is not assumed to be a primary direct determinant of the current operational farm size. Current farm size is more likely determined by the current operator's resources and prevailing market conditions, while a successor's influence on farm size would typically manifest in the future.

In the second stage, we estimated the farm size equation using a two-stage least squares (2SLS) approach. The IMR was included as a regressor to control for selection bias. Furthermore, following the procedure described in Wooldridge (2010), both the IMR and the number of days with less than 30 cm of snow depth served as instruments in the 2SLS estimation to simultaneously address the endogeneity of wild boar presence.

The results of this second-stage estimation are presented in Column (1) of Table A.7. The coefficient on the IMR is statistically significant, indicating the presence of sample selection bias and justifying the use of the Heckman procedure. Crucially, the negative effect of wild boar presence on farm size remains statistically significant even after accounting for potential sample selection bias. While the estimated magnitude is slightly attenuated relative to the primary estimation in Table 4, this result confirms the robustness of our finding to potential sample selection bias using the specific Heckman procedure based on Wooldridge (2010).

Additional Robustness Checks on Sample Definition and Aggregation—Beyond the Heckman procedure, we conducted further robustness checks concerning our sample definition and level of aggregation to ensure the stability of our findings. First, regarding our sample definition, our main analyses (including the Heckman procedure) focus on commercial farm households existing as of 2000, excluding farm households that newly emerged during the sample period. This approach was chosen because, based on the definition of a farm household in these data, it is unclear for newly appearing or disappearing households whether they truly started/stopped farming or simply fluctuated around the criteria defining a commercial farm household (e.g., transitioning to or from subsistence farming). To assess the robustness of our findings to this sample restriction, we re-estimated our models including these newly emerged farm households. As shown in Column (2) of Table A.7, our main results regarding the negative effect of wild boar presence on farm size remain robust even with this expanded sample.

Second, we performed robustness checks at the rural community level to examine the impact on the total number of farm households and the average operated area per household. For this analysis, we used aggregated data from the Rural Community Card and the World Census of Agriculture and Forestry. While these data do not provide information on each household, they allow us to capture community-level dynamics. As shown in Table A.8 in the online appendix, our results regarding the negative impact on average farm size also remain robust. These additional checks provide further confidence in our findings.

Alternative Approach: Long-Difference Model—Our main panel IV model with farm household and year fixed effects primarily identifies the impacts of changes in wild boar presence observed at 5-year intervals on farm exit and farm size. These estimates can be interpreted as relatively medium-run responses to the emerging wildlife conflict. However, in the longer-run, farmers' adjustments to persistent wild boar presence might differ if these medium-run effects are mediated through broader adaptation strategies. Therefore, to complement our panel IV estimates, and to further assess the robustness of our findings under different modeling assumptions, we follow Burke and Emerick (2016) and estimate a long differences regression of the form:

$$\Delta Ln\ (Farm\ size_{i,c}) = \gamma \Delta \widehat{Wild\ boar}_{i,c,2015} + \delta_p + \Delta v_{i,c}, \quad (4)$$

$$\Delta Wild\ boar_{i,c,2015} = \alpha \Delta Snow_{i,c} + \delta_p + \Delta \epsilon_{i,c} \quad (5)$$

where $\Delta Ln\ (Farm\ size_{i,c})$ is the change in operated farmland for farm household i in community c between two periods. We treated areas where farm household exits occurred as having zero operated farmland in the equation. $\Delta Snow_{i,c}$ term gives the change in the average number of days during winter (November–March) over the last five years when the snow depth did not exceed 30 cm over the two periods. These two periods are 2005 and 2015. For the 2005 –2015 period, we take averages for each variable over 2000–2005 and 2010–2015, and difference these two averages. We also included a prefecture fixed effect δ_p, which controls for any unobserved prefecture-level trends. This means that identification comes only from within-state variation, eliminating any concerns of time-trending unobservables at the prefecture level. Our results remained robust both with and without Hokkaido, as shown in Table A.9.

Mechanism

This subsection elucidates channels from the perspective of farm households' farmland use, explaining how wild boars reduce farm size. The preceding results consistently demonstrate an adverse effect of wild boars on farm size, giving rise to a valid question regarding the underlying mechanisms of this effect. If there are no costs associated with preventing wild boars, one can expect farm size to increase. This is because a decrease in the number of farm households leads to a greater concentration of farmland among the surviving farm households. However, if the cost of preventing wild boars is linked to operated farmland, abandoned farmland would increase, and rented-in farmland would decrease. To identify how the emergence of wild boars influences farm size, we use the same datasets and methodology described above to examine the impact on abandoned and rented-in farmland instead of using farm size as the dependent variable in the IV estimation. To address the more than two-thirds zero values in abandoned and rented farmland, we used a share of abandoned (or rented-in) farmland and the level of these variables (in hectares).

Table 5 presents the results regarding the impact on abandoned and rented-in farmlands. The coefficient for wild boars indicates a positive relationship with abandoned farmlands but a negative relationship with rented-in farmlands. These findings suggest that the emergence of wild boars reduces farm size by discouraging the increase in rented-in farmland and promoting an increase in abandoned farmland.

Table 5 The effect of channels of wild boars on farmland use

	Share of rented-in farmland	Rented-in farmland (ha)	Share of abandoned farmland	Abandoned farmland (ha)
	(1)	(2)	(3)	(4)
Second-stage				
Wild boar	-1.706 **	-0.298 ***	5.938 ***	0.091 **
	(0.814)	(0.099)	(1.620)	(0.038)
First-stage				
Number of days with less than 30 cm of snow depth	0.002 ***	0.002 ***	0.002 ***	0.002 ***
	(0.000)	(0.000)	(0.000)	(0.000)
Mean temperature in growing seasons and non-growing seasons	Yes	Yes	Yes	Yes
Mean temperature squared in growing seasons and non-growing seasons	Yes	Yes	Yes	Yes
Mean precipitation in growing seasons and non-growing seasons	Yes	Yes	Yes	Yes
Mean precipitation squared in growing seasons and non-growing seasons	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes
Farm household FE	Yes	Yes	Yes	Yes
Prefecture * Year FE	Yes	Yes	Yes	Yes
F (first stage)	75.58	75.58	75.58	75.58
Observations	1,019,815	1,019,815	1,019,815	1,019,815

Observations are farm households-year. SEs clustered at the farm household level and communituy level are in parentheses. Wild boar presence variables are dummies at the community level. ** $p < 0.05$, and *** $p < 0.01$.

Heterogeneity

Having established the negative effects of wild boars on farm size, we now examine the heterogeneity of these effects. Thus far, our analysis assumes that the impact of wild boar on farm exit and farmland use is identical across farming types. However, depending on the degree of reliance on farm income, the influence of wild boars on farm households' behavior may vary. Off-farm income provides greater stability than farm income and reduces the variability in the overall household income. While this income stability might support continued farming, off-farm income may also lower the barriers to exiting the farming sector, as suggested by Ramsey, Ghosh, and Sonoda (2019).For instance, it can reduce the perceived financial risk of leaving agriculture and potentially lessen the opportunity cost (i.e., foregone farm income relative to total income), thus making it easier for farm households to leave farming altogether. Thus, off-farm income can have competing effects on the decision to continue farming: while it provides income stability that may support farm operations, it can also lower the barriers to exiting agriculture. Consequently, the net impact of off-farm income on farm survival is theoretically ambiguous.

To explore this, we test for variations in the effects of wild boars on farm exit and farmland use by estimating them for subsamples categorized according to farm households' dependence on farm income. The sample is divided into part-time and full-time farm households based on their work status. Full-time farm households are defined as those who rely exclusively on farming as their primary source of income, with all members engaged solely in agriculture without any additional employment outside of farming. By contrast, part-time farm households are defined as those who engage in both farming and non-agricultural work with one or more household members employed outside of agriculture and with farm workers under 65 years of age. We used the same model in our base specifications, as presented in Table 4.

The results indicate that wild boar has a significant negative effect on the survival of part-time farm households but does not exhibit statistical significance for the survival of full-time farm households in columns (1) and (3) of Table 6. Columns (2) and (4) of Table 6 also reveal that wild boars significantly affect the farm size of part-time farm households but do not exhibit statistical significance for the farm size of full-time farm households.

Table 6 The effect of wild boars on farm survival and farm size: Heterogeneity

	Part-time farm households		Full-time farm households with farm workers under 65 years old	
	Farm survival (1)	Ln (Operated farmland) (2)	Farm survival (3)	Ln (Operated farmland) (4)
Second-stage				
Wild boar	-0.145 **	-0.147 ***	-0.150	-0.024
	(0.069)	(0.053)	(0.088)	(0.101)
First-stage				
Number of days with less than 30 cm of snow depth	0.002 ***	0.002 ***	0.002 ***	0.002 ***
	(0.000)	(0.000)	(0.000)	(0.000)
Mean temperature in growing seasons and non-growing seasons	Yes	Yes	Yes	Yes
Mean temperature squared in growing seasons and non-growing seasons	Yes	Yes	Yes	Yes
Mean precipitation in growing seasons and non-growing seasons	Yes	Yes	Yes	Yes
Mean precipitation squared in growing seasons and non-growing seasons	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes
Farm household FE	Yes	Yes	Yes	Yes
Prefecture * Year FE	Yes	Yes	Yes	Yes
F (first stage)	64.61	70.99	46.8	51.74
Observations	911,888	862,741	172,147	157,074

Observations are farm households-year. SEs clustered at the farm household level and communituy level are in parentheses. Farm survival is dummy. Wild boar presence variables are dummies at the community level. ** $p < 0.05$, and *** $p < 0.01$.Part-time farm households engage in both farming and non-agricultural work with one or more household members employed outside of agriculture. Full-time farm households rely exclusively on farming as their primary source of income, with all members engaged solely in agriculture without any additional employment outside of farming and with farm workers under 65 years of age.

These findings suggest that part-time households, which are less dependent on agriculture as a sole source of livelihood, are more susceptible to the adverse effects of wild boar damage. With additional income from non-farming employment, part-time farmers may find it easier to exit farming when faced with persistent wildlife issues. By contrast, full-time farmers—whose primary income relies on farming—are more motivated to continue farming despite the challenges posed by wild boars. Their reliance on agricultural income incentivizes them to invest in protective measures, such as fencing, traps, and deterrent techniques, which help mitigate boar-related damage and allow them to maintain their farm size. Furthermore, because of the centrality of farming in their livelihoods, full-time farm households often have greater flexibility to respond promptly to wildlife damage. By comparison, part-time farm households may face constraints in time resources, limiting their ability to implement effective protective measures and manage damage effectively. This situation may lead to increased boar-related damage and the consequent necessity to reduce farmland size. Our findings imply that the farmland of displaced and downsized part-time farm households is not being consolidated into the farmland of full-time farm households owing to the emergence of wild boars, which impedes structural change in agriculture.

6. Conclusion

Human–wildlife conflict poses substantial challenges to global agriculture, resulting in economic costs from crop raiding and carnivore-induced livestock depredation. These issues negatively impact agricultural production and sustainability. Climate change exacerbates human–wildlife conflicts by altering wildlife distribution and behavior. Shifts in temperature and precipitation patterns can cause changes in vegetation cover and food availability, enabling migration to new areas. The expanding wild boar distribution can increase the risk of conflicts and additional economic losses for farmers, threatening agricultural production and sustainability even worse.

This study shows the detrimental effects of wild boars on agricultural structural changes: farm survival and farm size. We examined the mechanism and heterogeneity effects using a unique panel dataset and exploit exogenous variation in the emergence of wild boars induced by changes in snow depth that heavily influence wild boar habitats. By employing IVs, we indicate that farm households in areas where wild boars are present are more likely to leave farming. Moreover, we found suggestive evidence of reduced farm size, as measured by operated farmland, in areas affected by wild boars than unaffected regions. Mechanism analysis reveals that the emergence of wild boars impels farm households to decrease farm size by increasing abandoned farmland and decreasing rented-in farmland. Furthermore, heterogeneity analysis shows that the impact of wild boars on farm survival and size varies by differences in reliance on farm income. In particular, wild boars impact part-time farm households. These results indicate that farmland is not being consolidated, with remaining full-time farmers, implying that structural change in agriculture is being hindered by wild boars.

The implications of this study are significant for Japan and other developed countries concerning the economic losses incurred in the agricultural sector owing to wildlife conflicts. The increase in wildlife-relevant conflicts is a global phenomenon resulting from the recent expansion of agricultural areas and changes in wildlife habitats. While wildlife has historically directly damaged agriculture through crop raiding and carnivore-induced livestock depredation, this study identified another crucial issue in rural areas: structural changes in agriculture caused by wildlife conflicts. Specifically, the emergence of wild boars, the focal point of this study, encourages farm households to abandon farming owing to additional costs and prevents the expansion of the farm size of surviving farm households. Given the long-term shifts in temperature and weather patterns caused by climate change, uncovering agricultural structural changes due to human–wildlife conflicts may be necessary to achieve a sustainable food supply. Therefore, it is recommended that agricultural policy measures be introduced to support affected farmers while considering the effect of wild boars on the declining number of farm households and farm size. To accomplish this, policymakers should review the undesirable structural changes that result from the increasing pressure of wild boars.

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ONLINE APPENDIX

Japanese Wild Boars Head North:

Snow Depth Decrease, Wildlife Conflict, and Structural Changes in Agriculture

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Table A.1 Data sources

	Source	Available years
Wild boar	Population Estimation and Habitat Distribution Survey of Japanese Deer, Ministry of the Environment	The 2003 survey (Survey period: 2000–2002), The 2011 survey (Survey period: 2007–2009), The 2014 survey (Survey period: 2012–1013)
Weather	Agro-Meteorological Grid Square Data (AMGSD), National Agriculture and Food Research Organization (NARO),	2000–2015
Farm household	Census of Agriculture and Forestry, Ministry of Agriculture, Forestry and Fisheries	2000, 2005, 2010, 2015
Community shapefile	Ministry of Agriculture, Forestry and Fisheries	2015

Population Estimation and Habitat Distribution Survey of Japanese deer: https://www.env.go.jp/press/109239.html. Agro-Meteorological Grid Square Data (AMGSD): https://amu.rd.naro.go.jp/wiki_open/doku.php?id=about. Census of Agriculture and Forestry, Ministry of Agriculture: These data are available upon application to the MAFF. Community shapefile: https://www.maff.go.jp/j/tokei/census/shuraku_data/2015/ma/index.html.
In Population Estimation and Habitat Distribution Survey of Japanese deer, the 2003 survey covers the habitat distribution from 2000 to 2002, the 2011 survey covers the habitat distribution from 2007 to 2009, and the 2014 survey covers the habitat distribution from 2012 to 2013.

Table A.2 Data acquisition year

Year	Census of Agriculture and Forestry	Population Estimation and Habitat Distribution Survey of Japanese deer
2000	The 2000 Census	Survey period (The 2003 survey)
2001		Survey period (The 2003 survey)
2002		Survey period (The 2003 survey)
2003		The 2003 survey
2004		
2005	The 2005 Census	
2006		
2007		Survey period (The 2011 survey)
2008		Survey period (The 2011 survey)
2009		Survey period (The 2011 survey)
2010	The 2010 Census	
2011		The 2011 survey
2012		Survey period (The 2014 survey)
2013		Survey period (The 2014 survey)
2014		The 2014 survey
2015	The 2015 Census	

Table A.3 Number of farm households as well as stayers and exiters farm households (all prefectures)

Year	Farm households	Stayers		Exiters	
	N	N	%	N	%
2000	1,500,964	1,196,404	79.7%	304,560	20.3%
2005	1,196,404	972,300	81.3%	224,104	18.7%
2010	972,300	772,622	79.5%	199,678	20.5%
2015	772,622				

Table A.4 Descriptive statistics by census year (Tohoku-Hokuriku regions and all prefectures)

Tohoku/Hokuriku regions	2000				2005				2010				2015			
	Mean	S.D.	Min	Max	Mean	S.D.	Min	Max	Mean	S.D.	Min	Max	Mean	S.D.	Min	Max
Panel A. Sample: Farm household in Tohoku and Hokuriku region																
Outcome																
Operated farmland (ha)	1.6	1.8	0.0	400.7	1.7	2.0	0.0	120.8	1.9	2.4	0.0	121.0	2.2	3.0	0.0	154.0
Rented-in farmland (ha)	0.2	1.1	0.0	400.0	0.3	1.3	0.0	116.3	0.4	1.6	0.0	108.4	0.6	2.1	0.0	120.0
Share of rented-in farmland	5.7	11.2	0.0	50.0	6.4	12.0	0.0	50.0	7.4	13.0	0.0	50.0	8.3	13.8	0.0	50.0
Abandoned farmland (ha)	0.1	0.2	0.0	20.0	0.1	0.3	0.0	63.5	0.1	0.3	0.0	27.5	0.1	0.3	0.0	35.3
Share of abandoned farmland	4.7	11.8	0.0	97.6	5.1	12.2	0.0	98.6	5.4	12.9	0.0	98.4	7.1	14.6	0.0	98.2
Treatment																
Wild boar presence dummy (1 if yes)					0.1				0.2				0.4			
Instrumental Variables																
Average number of days with less than 30 cm of snow depth for past 5years in winter					109.2	36.7	10.2	151.2	110.4	35.0	13.8	151.2	102.3	38.2	9.0	151.2
Sample size		515,492				421,190				335,945				262,680		
Panel B. Sample: Farm household in All prefectures																
Outcome																
Operated farmland (ha)	1.6	2.9	0.0	400.7	1.7	3.4	0.0	300.0	1.9	4.4	0.0	1496.0	2.2	4.7	0.0	573.6
Rented-in farmland (ha)	0.2	1.2	0.0	400.0	0.3	1.5	0.0	203.0	0.4	2.0	0.0	434.5	0.6	2.3	0.0	182.9
Share of rented-in farmland	6.3	11.8	0.0	50.0	7.0	12.5	0.0	50.0	7.9	13.3	0.0	50.0	8.5	13.9	0.0	50.0
Abandoned farmland (ha)	0.1	0.2	0.0	30.1	0.1	0.3	0.0	114.0	0.1	0.3	0.0	51.0	0.1	0.3	0.0	35.3
Share of abandoned farmland	5.2	12.5	0.0	98.1	5.5	12.9	0.0	99.0	5.5	13.1	0.0	99.3	6.8	14.5	0.0	99.3
Treatment																
Wild boar presence dummy (1 if yes)																
Instrumental Variables					0.5				0.5				0.6			
Average number of days with less than 30 cm of snow depth for past 5years in winter					131.7	33.3	8.2	151.2	132.9	31.9	13.6	151.2	130.0	35.5	9.0	151.2
Sample size		1,500,964				1,196,404				972,300				772,622		

Table A.5 The effect of wild boars on farm survival and farm size: Using the snow depth bin as IV

	Farm survival	Ln (Operated farmland)
	(1)	(2)
Second-stage		
Wild boar	-0.169 ***	-0.144 ***
	(0.055)	(0.044)
First-stage		
Number of days with less than 10-20cm cm of snow depth	0.001 **	0.001 ***
	(0.001)	(0.001)
Number of days with less than 20-30cm cm of snow depth	0.003 ***	0.002 ***
	(0.001)	(0.001)
Number of days with less than 30cm- of snow depth	-0.001 ***	-0.001 ***
	(0.000)	(0.000)
Mean temperature in growing seasons and non-growing seasons	Yes	Yes
Mean temperature squared in growing seasons and non-growing seasons	Yes	Yes
Mean precipitation in growing seasons and non-growing seasons	Yes	Yes
Mean precipitation squared in growing seasons and non-growing seasons	Yes	Yes
Controls	Yes	Yes
Farm household FE	Yes	Yes
Prefecture * Year FE	Yes	Yes
F (first stage)	32.91	35.43
Observations	1,272,627	1,019,815

Observations are farm households-year. SEs clustered at the farm household level are and communituy level in parentheses. Farm survival is a dummy. Wild boar presence variables are dummies at the community level. *** p < 0.01, and ** p < 0.05.

Table A.6 The effect of wild boars on farm survival and farm size: Using the number of days with less than 30 cm of snow depth for the past 7 years as IV

	Farm survival		Ln (Operated farmland)	
	(1)		(2)	
Second-stage				
Wild boar	-0.401	***	-0.342	***
	(0.088)		(0.065)	
First-stage				
Number of days with less than 30 cm of snow depth for past 7years	0.002	***	0.002	***
	(0.0002)		(0.0002)	
Mean temperature in growing seasons and non-growing seasons	Yes		Yes	
Mean temperature squared in growing seasons and non-growing seasons	Yes		Yes	
Mean precipitation in growing seasons and non-growing seasons	Yes		Yes	
Mean precipitation squared in growing seasons and non-growing seasons	Yes		Yes	
Temperature bin in growing seasons and non-growing seasons				
Precipitation bin in growing seasons and non-growing seasons				
Controls	Yes		Yes	
Farm household FE	Yes		Yes	
Prefecture * Year FE	Yes		Yes	
F (first stage)	48.25		61.15	
Observations	1,272,627		1,019,815	

Observations are farm households-year. SEs clustered at the farm household level and communituy level are in parentheses. Farm survival is a dummy. Wild boar presence variables are dummies at the community level. *** p < 0.0.

Table A.7 The effect of wild boars on farm size: Addressing sample selection and robustness

	Sample selection model	Sample with new emerged farm households
	(1)	(2)
Second-stage		
Wild boar	-0.118 ***	-0.150 ***
	(0.033)	(0.053)
Inverse mills ratio	-0.137 ***	
	(0.006)	
First-stage		
Number of days with less than 30 cm of snow depth	0.002 ***	0.002 ***
	(0.000)	(0.000)
Mean temperature in growing seasons and non-growing seasons	Yes	Yes
Mean temperature squared in growing seasons and non-growing seasons	Yes	Yes
Mean precipitation in growing seasons and non-growing seasons	Yes	Yes
Mean precipitation squared in growing seasons and non-growing seasons	Yes	Yes
Controls	Yes	Yes
Farm household FE	Yes	Yes
Prefecture * Year FE	Yes	Yes
F (first stage)	75.54	71.91
Observations	1,019,339	1,088,421

Observations are farm households-year. SEs for equation (1) [Heckman second stage] are obtained using a bootstrap method. SEs for equation (2), presented in parentheses, are clustered at the farm household. Equation (1) presents results from the second stage of a Heckman sample selection model. The first stage used a probit model to estimate the Inverse Mills Ratio (IMR).This probit model included a variable indicating the presence of a successor as an exclusion restriction. The second stage included the IMR as a regressor to control for selection bias and was estimated via 2SLS. Following the procedure recommended in Wooldridge (2010) for handling sample selection with an endogenous explanatory variable, both the IMR and the original excluded instrument ('Number of days with less than 30 cm of snow depth') served as instruments in this 2SLS estimation to simultaneously address selection bias and the endogeneity of wild boar presence. Wild boar presence variables are dummies at the community level. *** $p < 0.01$.

Table A.8 The effect of wild boars on farm numbers and farm size: Community-level analysis

	Ln (farm number)	Ln (farm size)
	(1)	(3)
Second-stage		
Wild boar	-0.199 **	-0.354 ***
	(0.085)	(0.088)
First-stage		
Number of days with less than 30 cm of snow depth	0.002 ***	0.002 ***
	(0.000)	(0.000)
Mean temperature in growing seasons and non-growing seasons	Yes	Yes
Mean temperature squared in growing seasons and non-growing seasons	Yes	Yes
Mean precipitation in growing seasons and non-growing seasons	Yes	Yes
Mean precipitation squared in growing seasons and non-growing seasons	Yes	Yes
Community FE	Yes	Yes
F (first stage)	89.84	60.17
Observations(community)	60,533	60,533

Observations are community-year. SEs clustered at communituy level are in parentheses. Wild boar presence variables are dummies at the community level. *** $p < 0.01$, and ** $p < 0.05$.

Table A.9 The effect of wild boars on farm size (long-difference estimates)

	IHS Operated farmland(ha)	
	Farm household in Tohoku and Hokuriku regions	Farm Household in Tohoku, Hokuriku, Hokkaido regions
	(1)	(2)
Second-stage		
Wild boar	-0.255 ***	-0.260 **
	(0.092)	(0.112)
First-stage		
Number of days with less than 30 cm of snow depth	0.002 ***	0.002 ***
	(0.001)	(0.000)
Mean temperature in growing seasons and non-growing seasons	Yes	Yes
Mean temperature squared in growing seasons and non-growing seasons	Yes	Yes
Mean precipitation in growing seasons and non-growing seasons	Yes	Yes
Mean precipitation squared in growing seasons and non-growing seasons	Yes	Yes
Prefecture fixed effects	Yes	Yes
Controls	Yes	Yes
F (first stage)	13.27	10.41
Observations	514,935	561,778

Observations are farm households-year. SEs clustered at the communituy level are in parentheses. Wild boar presence variables are dummies at the community level. *** p < 0.01, and ** p < 0.05.