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ARTICLE

Wild pigs (*Sus scrofa*) population management in Brazil: economic, land use, and greenhouse gas emissions impacts

Manejo de javalis (Sus scrofa) no Brasil: impactos na economia, no uso da terra e nas emissões de gases de efeito estufa

Giovani William Gianetti[1*], Carla Grasiele Zanin Hegel[2], Joaquim Bento de Souza Ferreira Filho[3]

[1]Grupo de Políticas Públicas, Escola Superior de Agricultura "Luiz de Queiroz" (ESALQ), Universidade de São Paulo (USP), Piracicaba (SP), Brasil. E-mail: giovani.gianetti@gmail.com

[2]Departamento de Zoologia, Universidade de Brasília, Brasília (DF), Brasil. E-mail: carlinhahehe@yahoo.com.br

[3]Departamento de Economia, Administração e Sociologia, Programa de Pós-graduação em Economia Aplicada, Escola Superior de Agricultura "Luiz de Queiroz" (ESALQ), Universidade de São Paulo (USP), Piracicaba (SP), Brasil. E-mail: jbsferre@usp.br

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Abstract: This study systematically assesses the impact of wild pig population control on avoidable crop losses in Brazil, along with its economic and environmental implications. By utilizing the TERM-BR15 Computable General Equilibrium model, we conducted simulations for the period from 2023 to 2030. We developed three scenarios that focus on increased yields of corn, soybeans, and sugarcane while varying the intensity of avoidable damage caused by wild pigs through adjustments to parameters such as pig harvest rates and average daily crop intake. The intermediate scenario forecasts a 0.15% increase in Gross Domestic Product (GDP) and a 0.17% rise in real household consumption compared to the baseline of 2030, resulting from effective wild pig population management. This equates to an increase of approximately US$203.18 in GDP and US$151.49 in household consumption for each wild pig managed (based on a BRL to US$ exchange rate of 5). The national output for corn, soybeans, and sugarcane is expected to rise, accompanied by reductions in greenhouse gas emissions intensity and deforestation. Although real GDP is expected to increase across all Brazilian regions, areas not impacted by wild pigs may see a decline in grain production. Our findings offer an evidence-based estimate of the economic and environmental impacts of wild pig crop damage, providing valuable insights for the formulation of public policies aimed at addressing this challenge.

Keywords: wildlife management, wild boar, feral hogs, pest control, computable general equilibrium.

Resumo: Este estudo avalia sistematicamente o impacto do controle populacional de javalis sobre as perdas agrícolas evitáveis no Brasil, assim como suas implicações econômicas e ambientais. Utilizando o modelo de Equilíbrio Geral Computável TERM-BR15, foram realizadas simulações para o período de 2023 a 2030. Foram desenvolvidos três cenários de aumento da produtividade de milho, soja e cana-de-açúcar, variando a intensidade dos danos evitáveis causados pelos javalis por meio de ajustes em parâmetros como taxas de abate de javalis e a ingestão diária média de lavouras. O cenário intermediário mostrou um aumento de 0,15% no Produto Interno Bruto (PIB) e um crescimento de 0,17% no consumo real das famílias, em comparação ao cenário base de 2030, atribuído ao manejo populacional de javalis. Isso equivale a um aumento de aproximadamente R$ 1.015,90 no PIB e R$ 757,45 no consumo das famílias para cada javali manejado. A produção nacional de milho, soja e cana-de-açúcar aumentaria, acompanhada por reduções na intensidade das emissões de gases de efeito estufa e no desmatamento. Embora o PIB real deva aumentar em todas as regiões do Brasil, áreas não impactadas pelos javalis podem observar uma diminuição na produção de grãos. Os resultados apresentados oferecem uma estimativa baseada em evidências dos impactos econômicos e ambientais dos danos agrícolas causados pelos javalis, o que pode subsidiar políticas públicas para enfrentar essa questão.

Palavras-chave: manejo de fauna, porcos asselvajados, controle de pragas, equilíbrio geral computável.

1. Introduction

The wild pig (*Sus scrofa*) is a species native to Eurasia and North Africa. However, it has been introduced worldwide for commercial and hunting purposes (West et al., 2009; Hegel et al., 2022). This species exhibits resilience and adaptability to a variety of edaphoclimatic conditions (Baskin & Danell, 2003). Its adaptability is enhanced by its high reproduction rates, omnivorous diet, and minimal predation pressure, particularly in non-native habitats (Barrios-Garcia & Ballari, 2012).

Wild pigs exhibit a range of behavioral traits, such as rooting and wallowing, which have diverse impacts on both fauna and flora. These behaviors can alter the soil's physical, biological, and chemical properties, thereby affecting water quality and vegetation cover (Massei & Genov, 2004). Additionally, these behaviors influence wildlife population dynamics, habitat integrity, and nesting opportunities (Ickes et al., 2005; Barrios-Garcia & Ballari, 2012). Wild pigs create challenges for native species by competing for resources and potentially facilitating the spread of diseases (Hegel et al., 2019b). Furthermore, their access to abundant food sources resulting from agricultural expansion allows them to consume crops and livestock, directly impacting the profitability and productivity of farms. This situation underscores the growing need for effective species management.

Managing the wild pig population poses a significant challenge for Brazil, a leading global producer of commodities such as soybeans, corn, cotton, oranges, poultry, and beef. From 2011 to 2020, Brazil's agricultural production grew at an annual rate of 3.1%, with Total Factor Productivity in agriculture increasing by 2.0% per year – almost double the global average of 1.1% (Organization for Economic Cooperation and Development, 2023). Throughout this period, the wild pig population in Brazil has been steadily rising (Hegel et al., 2022), resulting in its classification as a pest. In 2013, the Brazilian Wildlife Department (Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis – IBAMA) designated wild pigs as an invasive and dangerous species (Brasil, 2013).

To control the wild pig population, authorized hunters[1] who are registered with IBAMA are permitted to manage these animals without specific quotas or seasonal restrictions (Brasil, 2023a). However, the commercial use of wild pig carcasses and by-products is prohibited, which means that the economic value derived from harvesting[2] wild pigs is solely linked to its impact on agricultural production and land value. This is a significant factor, as the potential benefits of harvesting may influence hunters' perceptions of the population and affect the spread and presence of wild pigs (McLean et al., 2021; Smith et al., 2023). Starting in 2020, the number of registered hunters with IBAMA experienced a significant rise, soaring from 24,611 in 2020 to 61,015 by 2022. The recorded harvest of wild pigs also experienced growth, jumping from approximately 78,718 in 2020 to 153,430 in 2022, which represents a remarkable 97.4% increase (Brasil, 2023b)[3]. However, a change in government policy in 2023 led to a temporary ban on firearm-based harvesting from July to December of that year (Brasil, 2023c). This measure may result in a surge in the wild pig population, potentially exacerbating damage to crop production and the environment. This demonstrates the dependence of wild pig population control on

[1] For hunters utilizing firearms, additional authorization from the Brazilian Army is required. This process entails stringent criteria, including being over 25 years old, possessing a clean criminal record, providing proof of legal employment, demonstrating fixed residence for at least five years, and passing psychological and firearm handling aptitude tests, among other prerequisites (Brasil, 2023a).

[2] "Harvesting wild pigs" refers to the intentional removal or killing of wild pigs from the environment, typically as a method of population control.

[3] Request for personal information to IBAMA: The database included duplicated total harvest amounts for each management authorization, with each line reflecting reported animal characteristics (weight, size, gender, and stage of development). Our request for supplementary information was denied. We refined the database by eliminating duplicates based on date, municipality, report date, authorization query date, and harvest occurrence.

regulatory changes, executive orders, and laws, all of which are subject to fluctuating levels of restriction or leniency.

Previous studies in Brazil have concentrated on evaluating harvesting practices (Rosa et al., 2018; Carvalho et al., 2019). These investigations explored various aspects, including the average number of wild pigs harvested, the motivations behind control efforts, and the legal framework governing harvesting activities. Additionally, Pedrosa et al. (2015), Martins et al. (2019) and Hegel et al. (2019a, 2022) investigated the population dynamics and behavioral patterns of wild pigs, including their habitat preferences and spatial distribution. Moreover, Cervo & Guadagnin (2020) and Pedrosa et al. (2021) conducted research on the dietary habits of wild pigs in Brazil. Their findings indicated that over 90% of the wild pig diet consists of plant matter, with crops accounting for at least 40% of their intake, except in the Pantanal biome.

Research on wild pigs in Brazil has yet to yield a comprehensive evaluation of population density, comparable to the in-depth analysis conducted by Bieber & Ruf (2005), which investigates asymptotic growth rates under diverse environmental and biological conditions. Currently, there is no official or systematically collected data regarding the estimated size of the wild pig population in Brazil. Furthermore, evaluations addressing crop damages and their integrated socioeconomic effects, as examined by Anderson et al. (2016) and Holderieath et al. (2022), are limited in the Brazilian context. Among the existing studies, Lobo (2022) offers estimates of harvest efforts, surveys assessing crop damage, and simulations of the economic impact caused by wild pigs in a hypothetical setting.

This study presents a novel economic modeling approach to evaluate the wild pig hazard in Brazil, incorporating three population management scenarios and their direct impact on crop losses. Variations in crop loss affect agricultural markets and land productivity, with far-reaching implications for the allocation of primary production factors, land use dynamics, economic growth, household welfare, and greenhouse gas (GHG) emissions. To capture these interconnected effects, we employed a Computable General Equilibrium (CGE) model covering the period from 2023 to 2030. This study enhances the existing literature on wild pig management in Brazil by systematically quantifying the economic and environmental benefits of preventing crop losses through effective population control.

2. Theoretical foundation

The effects of wild pigs on native fauna and flora have been thoroughly documented in the literature, with notable studies conducted by Massei & Genov (2004), Ickes et al. (2005), West et al. (2009), Barrios-Garcia & Ballari (2012), and Hegel et al. (2019a, 2019b, 2022). Economic impacts have been mainly evaluated through agricultural production losses, utilizing survey-based methodologies, as demonstrated in research by Anderson et al. (2016), Poudyal et al. (2017), Gren et al. (2019), Pereira et al. (2019), McKee et al. (2020), Lobo (2022), and Tian et al. (2023). Furthermore, Holderieath et al. (2018, 2022) broadened the analytical scope by analyzing additional dimensions of this issue, including welfare losses for both consumers and farmers.

Lobo (2022) conducted an online survey in Brazil with 135 valid respondents, finding that 89% were aware of wild pigs in their municipality, 80% reported sightings on personal property, and 67% had implemented measures for population management. Utilizing the methodology developed by Anderson et al. (2016), Lobo estimated crop damage in 2020 for the Southeast, Midwest, and South regions of Brazil, revealing losses ranging from 8.7%, 5.9%, and 8.8% for corn; 4.0%, 1.8%, and 1.7% for soybeans; and 4.2% and 0.6% for sugarcane, respectively. The study also identified that lower thermal amplitude and latitude were negatively associated with the likelihood of wild pig presence in municipalities. Conversely, factors such as higher crop suitability, cultivation of crops, planted forests, pastures, and increased distance from roads were associated with a greater probability of wild pig sightings.

Pereira et al. (2019) conducted a survey with 210 residents living near a national park in Brazil, revealing that 94% of participants reported significant crop damage attributed to wild pigs. The financial losses reported ranged from US$500 to US$3,000. However, the study did not include details on the total area of crops impacted or provide estimates of the wild pig population within the park.

Assessments of wild pig damage are more commonly conducted in the United States than in other regions. A survey by Poudyal et al. (2017) in Tennessee revealed that 66% of landowners had experienced damage caused by wild pigs. Similarly, Mengak (2016, as cited in Poudyal et al., 2017) reported that 43% of landowners had suffered losses due to these animals. Additionally, Poudyal et al. also referenced estimates of crop damage across various states, noting that Texas incurred approximately US$ 52 million in losses (Texas A&M, 2012, as cited in Poudyal et al., 2017), while Georgia faced losses around US$ 150.5 million (Mengak, 2016, as cited in Poudyal et al., 2017). These figures underscore the substantial scale of the wild pig problem throughout the United States.

Anderson et al. (2016) estimated that annual losses from wild pigs amounted to US$ 190 million in 2014, affecting six major crops – corn, soybeans, wheat, rice, peanuts, and sorghum – across 11 states in the United States. The prevalence of wild pigs on agricultural land varied significantly, ranging from 5% in Missouri to 67% in Georgia, with corresponding reports of crop damage between 2% and 51%. These findings highlight a strong correlation between the presence of wild pigs and the level of agricultural damage. Hunting activities were also prevalent, with participation levels ranging from 20% in California to 62% in Georgia, where “shoot on sight” emerged as the most commonly employed method. McKee et al. (2020) further expanded the analysis to include “second-tier” crops such as hay, pecans, melons, honeydew, watermelon, sugarcane, sweet potatoes, and cotton, across 12 states in the United States, estimating an annual crop loss of US$272 million. In 2018, 34% of landowners reported utilizing at least one control method, with 26% resorting to “shoot on sight” as their primary strategy. The prevalence of wild pigs varied from 1% in Missouri to 78% in Texas, and crop damage reports ranging from 0% to 59% in the same states. Likewise, hunting rates showed significant variation, spanning from 5% in Missouri to 75% in Texas.

Tian et al. (2023) conducted a survey across Arkansas, Louisiana, and Texas to evaluate the economic impact of wild pig damage in 2021. Their findings revealed average losses per hectare: US$67.13 for cropland, US$42.96 for forestland, US$27.31 for pastureland, and US$57.54 for multiple land types. Notably, no statistically significant differences in total losses were identified among the three states. In terms of crop damage, soybeans were the most affected in Arkansas (57.3%) and Louisiana (44.7%), while in East Texas, silage and forage crops experienced the most significant impacts, with 87.3% of respondents reporting damage. Additionally, corn emerged as the second most affected crop in Arkansas and Louisiana, as indicated by over 35% of respondents.

Gren et al. (2019) examined the impacts of wild pigs in Sweden and found that 39% of surveyed farmers reported experiencing damages. Their statistical analysis revealed that costs correlated positively with wild pig abundance and landscape diversity, while inversely relating to the proportion of grain production. This decrease was attributed to reduced food availability during winter months. Of the total estimated damages, amounting to US$36.14 per hectare, 63% were attributed to crop losses, 9% to machinery damage, and 28% to protective measures.

Holderieath et al. (2018, 2022) contributed to the literature by examining the net short-run and long-run welfare effects of wild pig damage on both consumers and farmers in the United

States. In their 2018 study, the authors estimated that mitigating wild pig damage to key crops, including corn, soybeans, wheat, rice, and peanuts, would yield a net surplus of US$142 million in the short run and US$89 million in the long run. Conversely, farmers in unaffected regions would incur losses of US$65 million and US$13 million, respectively, due to the resulting decrease in market prices driven by increased supply. In a subsequent study, Holderieath et al. (2022) projected potential annual welfare losses ranging from US$54 million to US$350 million if wild pigs were to expand northward. Both studies primarily focused on direct changes in output and their price implications. Nevertheless, the wider general equilibrium effects of wild pig-related productivity losses in agriculture, such as impacts on land use and GHG emissions, have yet to be examined in the existing literature.

3. Methodology

We utilized a computable, dynamic, interregional, and bottom-up general equilibrium model known as The Enormous Regional Model for the Brazilian Economy (TERM-BR) to simulate scenarios for the period from 2023 to 2030. The TERM-BR15 is calibrated for 2015 and has been updated through historical simulations up to 2022, building on the research conducted by Gianetti & Ferreira Filho (2024).

In dynamic modeling, investment and capital are determined endogenously, reflecting the economy's behavior during the implementation of policies. As an inter-regional and bottom-up model, equilibrium is achieved across all 26 states and the Federal District in Brazil, which are interconnected through markets for goods, services, and production factors. Regional variables, such as household consumption and labor, are influenced by regional income levels and fluctuations in relative real wages. Economic agents, including households and firms, aim to maximize their utility and profit, respectively, while adhering to budget constraints and production functions. National-level results are derived by aggregating regional outcomes.

TERM-BR15 employs a diagonalized production technology involving 38 firms that produce 38 distinct goods or services (Table 1). Each firm combines intermediate inputs, production factors, and various costs, such as taxes, utilizing a Leontief function. The optimization of the model is guided by nested production functions that facilitate the substitution of imported and domestic goods, decisions regarding domestic regions, primary composition of primary factors, and other components, employing Constant Elasticity of Substitution (CES) functions.

Land use for agriculture is integrated into economic modeling through a transition matrix approach, which allows land to shift among four broad categories: agriculture, pastures, planted forests, and unused areas across Brazil's six biomes and 27 regions (including the 26 states and the Federal District). These transitions are governed by probabilities based on historical land use changes (Gianetti & Ferreira Filho, 2024). Variations in the rate of return from agricultural activities and technological factors endogenously influence these transition probabilities, which are based on land use type, biome, and region. Additionally, farming and pasture lands are allocated to specific production activities, such as soybean cultivation or livestock production, depending on their relative profitability, and modeled using Constant Elasticity of Transformation (CET) functions. The model includes two GHG emissions modules. The first module accounts for emissions stemming from fuel consumption and other productive activities, while the second focuses on land use, land use change, and forestry (LULUCF). This module estimates emissions resulting from land-use transitions, land stock availability, and deforestation rates across the defined land use categories, biomes, and regions in Brazil. To reduce computational complexity and facilitate analysis, the original 27 regions in Brazil have been aggregated into 15, as outlined in Table 2.

Table 1. TERM-BR15 activities and products

Activities/products	Description
Rice	Rice, wheat, and other grains
Corn	Corn
Cotton	Herbaceous cotton and other fiber crops
Sugar cane	Sugar cane
Soybean	Soybean
Other annual crops	Other annual crops and services
Citrus	Citrus
Coffee	Coffee
Other permanent crops	Other permanent crops and services
Beef cattle	Cattle and other live animals
Dairy cattle	Milk from cows and other animals
Pork	Pork
Poultry	Poultry and eggs
Forestry	Forestry
Fishing	Fishing and aquaculture
Mining	Mineral coal, iron ore, and others
Slaughter	Beef, pork, poultry, and processed fish
Processes food	Pasteurized milk, dairy products, sugar, vegetable and animal oils, processed grains, and other food and beverages
Agroindustry (non-food)	Animal feed, tobacco, textiles, wood products, and others
Other manufactured	Paper, rubber, plastic, cement, and other products
Gasoline C	Gasoline C
Ethanol	Ethanol and other biofuels
Other fuel	Aviation fuels, Diesel, and other petroleum refinery products
Chemical	Inorganic and organic chemical products, fertilizers, paints, perfumery, pharmaceuticals, and other chemicals
Metallurgy	Steel, iron, and other metals products
Electrical and electronic	Electronic components, appliances and materials
Automobiles	Automobiles, tractors, aircrafts, and other transport equipment
Electricity and gas	Electricity, gas and other utilities
Water and waste	Water, sewage, recycling and waste management
Construction	Buildings and construction services
Trade	Trade
Transport	Transportation services
Hotel and food	Hotel and food services
Communication	Newspaper, telecommunications, and other services
Health and education	Health and education services
Public administration	Public administration
Domestic services	Domestic services
Other services	Services not listed above

Source: Gianetti & Ferreira Filho (2024).

Table 2. TERM-BR15 aggregation of the Brazilian states

TERM-BR15 regions	Brazilian states	Macro regions
Rondonia	Rondônia	North
AmazACRR	Acre, Amazonas and Roraima	
ParaAP	Pará and Amapá	
MaToPi	Maranhão, Tocantins and Piauí	North/Northeast
RNordeste	Ceará, Rio Grande do Norte, Paraíba, Pernambuco, Alagoas and Sergipe	Northeast
Bahia	Bahia	
MinasG	Minas Gerais	Southeast
RSudeste	Espírito Santo and Rio de Janeiro	
SaoPaulo	São Paulo	
Parana	Paraná	South
RSul	Santa Catarina and Rio Grande do Sul	
MtGrSul	Mato Grosso do Sul	Mid-West
MtGrosso	Mato Grosso	
GoiasDF	Goiás and Distrito Federal	

Source: Gianetti & Ferreira Filho (2024).

3.1. Simulation Strategy

We adopted a three-step simulation strategy to establish baseline scenarios for the period from 2023 to 2030 (Figure 1). First, we replicated the historical behavior of the economy from the model's base year (2015) through 2023, utilizing observed macroeconomic data from Gianetti & Ferreira Filho (2024). Next, we projected a business-as-usual (BAU) trajectory for the economy from 2023 to 2030, based on macroeconomic forecasts provided by the same source. These projections incorporated the assumption that wild pig population control strategies were integrated into national trends in macroeconomic performance, crop yields, and land use changes. This assumption aligns with the regulatory framework in effect in the TERM-BR model base year (2015), when wild pig harvesting was legally permitted in Brazil. In the third step, we introduced crop damage shocks to corn, soybean, and sugarcane production based on projected wild pig population growth from 2023 to 2030. This approach enabled a comparison between unmanaged and managed population scenarios modeled under three distinct levels of damage intensity[4]. Consequently, three separate baseline projections for the Brazilian economy in 2030 were generated, each reflecting a different assumption regarding the growth of the wild pig population in the absence of management.

We subsequently simulated policy scenarios that involved increased outputs of corn, soybeans, and sugarcane, aligned with three levels of wild pig population control intensity. This approach demonstrated the economic advantages of population management relative to the losses experienced under unmanaged conditions. Simulating a business-as-usual (BAU) scenario with

[4] It is worth noting that McLean et al. (2021) found that wild pig damage was not a strong predictor of hunters' tolerance. However, their study did not account for the potential long-term effects of increasing frequency and severity of wild pig damage on tolerance, which could influence landowners' and hunters' compliance with harvesting prohibitions. This factor was not assessed in our simulation scenarios.

endogenously determined crop production was crucial, as it established a reference point for assessing the baseline economic impacts of wild pig damage and for comparing these impacts against the benefits derived from implementing control measures.

In the simulation strategy, 2023 serves as the intervention year, at which point a decision is made regarding whether to prohibit management (represented by the baselines) or to actively manage the wild pig population (represented by the policy scenarios). This decision will result in varying levels of wild pig populations and associated damages from 2023 to 2030. The cumulative differences observed by 2030 between the policy scenarios and the baselines will illustrate the potential impacts of managing the wild pig population compared to a scenario of no management.

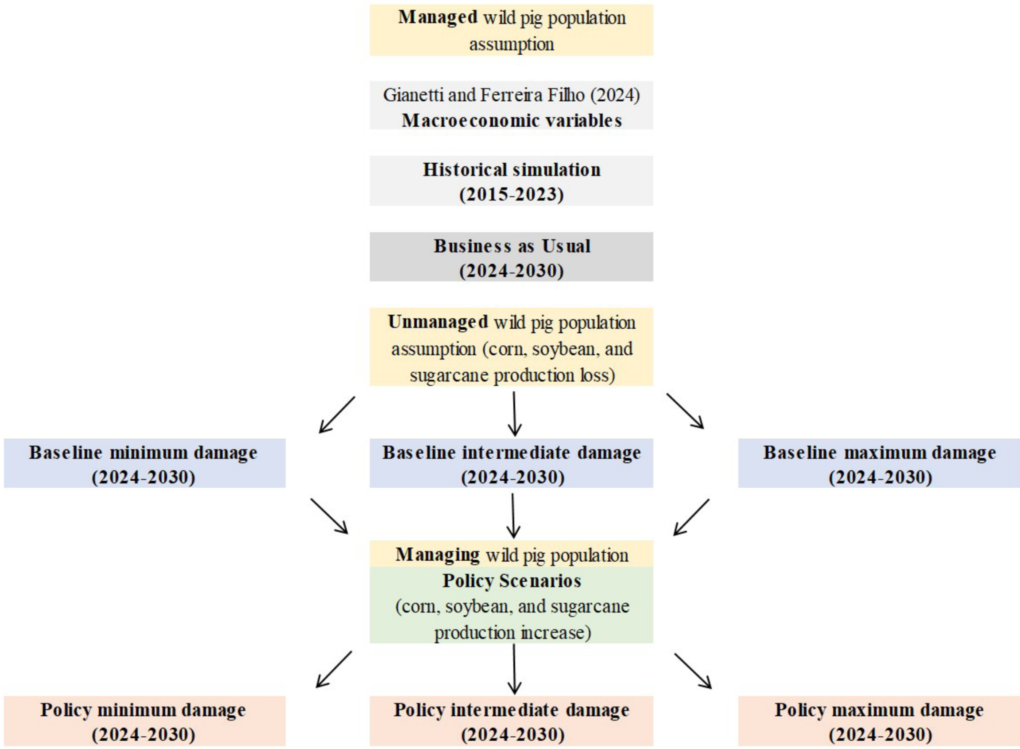

Figure 1. Simulation strategy. Source: The authors.

3.2. Baseline simulations

Crop damage simulations were confined to Brazil's Midwest, Southeast, and South regions[5]. Projections for the regional wild pig population in 2022 were based on observed population management data, utilizing assumed harvest rates of 25%, 33%, and 50% of the total population. These rates reflect female wild pig mortality, a crucial factor influencing population dynamics, as reported by IBAMA and discussed in Hegel (2021). To estimate differences between managed and unmanaged population scenarios, we adopted annual asymptotic growth rates of 9% and 63%, respectively, following the methodology established by Bieber & Ruf (2005). Although the 63% growth rate may seem exceptionally high, it is corroborated by studies such as Gren et al.

[5] Although wild pigs are present in the North and Northeast regions, they collectively accounted for only 0.5% of the total wild pig harvest between April 2019 and July 2023.

(2016), which estimated an average intrinsic growth rate of 48% for the wild pig population in Sweden from 2004 to 2011.

We assessed crop damage to corn, sugarcane, and soybeans based on the dietary preferences of wild pigs, referencing research by Pedrosa et al. (2021) for corn and sugarcane, and Cervo & Guadagnin (2020) for soybeans. Over four months each year, corn constituted approximately 61.7% of the wild pig diet, while soybeans and sugarcane[6] contributed 45%[7] and 15.8%, respectively. Crop consumption was calculated using a daily intake rate of 3% to 5% of the animal's body weight (Bodenchuk, 2008), along with average body weights gleaned from harvested wild pig data (Brasil, 2023b). These parameters allowed for the estimation of the crop damage inflicted by an unmanaged wild pig population in comparison to the business-as-usual (BAU) scenario. This methodology aligns with findings by Gren et al. (2019), which indicate a positive correlation between the presence of wild pigs and the degree of agricultural damage. Consequently, we simulated three baseline scenarios. Baseline shocks were derived from the projected annual growth of wild pig populations under unmanaged conditions, estimated to range from 1.93 to 3.85 million animals above levels projected under management. This population surge resulted in estimated crop losses ranging from 596.9 to 1,989.6 thousand tons (Table 3).

Table 3. Wild pig population growth and crop damage in projections

Scenarios	Harvest rate	Wild pig diet	Annual average of variables	Projections	
				Managed Population	Unmanaged Population
Minimum damage	50%	3% of body weight daily	Population Growth (1,000 wild pigs)	43.4	1,968.5
			Crop damage (1,000 tons)	13.2	596.9
Intermediate damage	33%	4% of body weight daily	Population Growth (1,000 wild pigs)	65.8	2,982.6
			Crop damage (1,000 tons)	26.6	1,205.8
Maximum damage	25%	5% of body weight daily	Population Growth (1,000 wild pigs)	86.8	3,937.0
			Crop damage (1,000 tons)	43.9	1,989.6

Source: The authors.

3.3. Policy Shocks

To assess the impacts of wild pig management, we conducted policy shock analyses that simulate increases in corn, soybean, and sugarcane production under population control measures for the period from 2023 to 2030. These policy shocks are detailed in Table 4. The regional distribution of these shocks was informed by estimates of wild pig populations and crop yields. The wild pig population estimates were based on the percentage of animals harvested

[6] Applied specifically to Paraná and São Paulo states, regions where wild pig damage to sugarcane crops is more prevalent.

[7] Cervo & Guadagnin (2020) found that the stomach contents of wild pigs in the Araucaria Forest comprised 44.4% cultivated grains, while in the Pampa region, the figure was 48.1%. Given that soybeans are the predominant crop in Brazil, covering more than 41 million hectares and accounting for 48% of the annual cultivated area, we estimated that soybeans constitute approximately 45% of the wild pig diet for one-third of the year.

in 2023[8] (Table 5), utilizing the most recent data available from Brasil (2023b). Crop output was calibrated using the TERM-BR15 model along with corresponding simulations. Consequently, the scale of the production shocks was influenced by the relationship between estimated crop damage and regional crop yields. Areas with higher wild pig harvest rates, such as Rio Grande do Sul, which accounted for 28.6% of the national total, experienced more substantial production increase shocks. The Southern region of Brazil first officially reported wild pig dispersion in the late 1980s, although unofficial accounts trace the presence of wild pigs in the area to the 1960s (Deberdt & Scherer, 2007; Salvador, 2012).

Table 4. Annual average percentage crop production shocks in the policy scenarios of minimum, intermediate, and maximum damage.

Regions	Minimum			Intermediate			Maximum		
	Corn	Soybeans	Sugarcane	Corn	Soybeans	Sugarcane	Corn	Soybeans	Sugarcane
MinasG	1.88	1.31	0.00	3.91	2.71	0.00	6.72	4.59	0.00
SaoPaulo	1.80	1.32	0.004	3.75	2.73	0.01	6.43	4.62	0.01
Parana	0.40	0.32	0.04	0.81	0.65	0.08	1.35	1.08	0.14
Rsul	4.87	1.43	0.00	10.68	2.95	0.00	19.97	5.02	0.00
MtGrSul	0.96	1.02	0.00	1.98	2.09	0.00	3.33	3.52	0.00
MtGrosso	0.05	0.04	0.00	0.11	0.08	0.00	0.18	0.13	0.00
GoiasDF	0.91	0.46	0.00	1.86	0.93	0.00	3.13	1.55	0.00
Brazil	0.77	0.44	0.01	1.52	0.88	0.01	2.43	1.44	0.02

Source: The authors.

Table 5. Wild pig harvested from January to July 2023.

Regions	Harvested animals	% Harvested
MinasG	34,259	18.67
SaoPaulo	20,087	10.95
Parana	13,881	7.57
Rsul	52,474	28.60
MtGrSul	31,209	17.01
MtGrosso	5,713	3.11
GoiasDF	24,675	13.45
Others	1,157	0.63
Brazil	183,455	100.00

Source: The authors. Data from Brasil (2023b).

Regions such as Mato Grosso, which accounted for only 3.11% of wild pig harvests, experienced relatively minor production shocks. While Mato Grosso is Brazil's largest grain-producing state and could potentially see significant wild pig expansion without population control, the estimates of shocks were conservatively derived from the region's initial share of

[8] This relationship may be attributed to landowners' desire to control wild pigs due to their perception of economic and environmental damages these animals cause (Caplenor et al., 2017; Watkins et al., 2019). Consequently, increased harvesting efforts could signal higher prevalence of observed damage and larger populations of wild pigs.

wild pig harvests. This methodology promoted consistency across areas and aligned with the most recent available data.

4. Results and Discussion

4.1. National impacts

Effective management of the wild pig population in Brazil contributes to higher production levels of corn, soybeans, and sugarcane (Table 6), driven by productivity gains in the model. The efficient use of agricultural inputs, such as seeds, fertilizers, and pesticides, can be improved by minimizing crop losses attributed to wild pigs. In turn, the greenhouse gas (GHG) emission intensity, which refers to emissions per unit of output, declines for these crops (Table 6).

Corn is the most significantly affected crop, primarily due to its substantial presence in the wild pig diet. Output increases are projected to range from 5.49% to 18.33%, with corresponding reductions in GHG emission intensity between 1.56% and 4.97% across the various management scenarios compared to the 2030 baseline. Soybean production is expected to rise by 3.12% to 10.52%, accompanied by a decrease in GHG emission intensity ranging from 0.85% to 2.72%. In contrast, sugarcane is projected to experience a more modest increase in output, with projections ranging from 0.04% to 0.15%, along with reductions in GHG emission intensity from 0.09% to 0.29%.

These findings underscore the substantial impact that managing wild pig populations can have on Brazil's efforts to meet its Sustainable Development Goals and uphold its commitments under the Paris Agreement (Brasil, 2022). Additionally, our analysis does not consider the GHG emissions directly associated with the wild pig population, which could also be mitigated through effective population control measures.

Table 6. Simulation results, crop output and greenhouse gas (GHG) emission intensity accumulated percentage difference from the 2030 baseline.

Crops	Minimum		Intermediate		Maximum	
	Output	Emissions intensity	Output	Emissions intensity	Output	Emissions intensity
Corn	5.49	-1.56	11.10	-3.09	18.33	-4.97
Soybeans	3.12	-0.85	6.33	-1.69	10.52	-2.72
Sugarcane	0.04	-0.09	0.08	-0.18	0.14	-0.29

Source: The authors.

Effective management of wild pig populations enhances crop yields, which in turn stimulates broader economic activity. This leads to real GDP growth ranging from 0.08% to 0.24% across the three scenarios by 2030, relative to the baseline (Table 7). In financial terms, this translates to GDP increases between US$2.1 billion and US$6.7 billion, based on an exchange rate of BRL 5 per US dollar, under the minimum and maximum crop damage scenarios, respectively. These gains yield average net GDP benefits of US$155.94, US$203.18, and US$246.44 per wild pig harvested in the minimum, intermediate, and maximum scenarios, respectively. When applied to the total area dedicated to the cultivation of corn, soybeans, and sugarcane in regions affected by wild pigs, this results in an average annual GDP increase of US$5.50, US$10.84, and US$17.35 per hectare, respectively.

Our findings, which account for general equilibrium effects, suggest the impacts on the GDP may exceed those reported by previous studies, including those by Anderson et al. (2016), Poudyal et al. (2017), Holderieath et al. (2018, 2022), Gren et al. (2019), Pereira et al. (2019), McKee et al. (2020), Lobo (2022), and Tian et al. (2023)[9]. Furthermore, the potential economic benefits associated with wild pig management could be even more substantial if additional factors, such as damage to 'second-tier' crops (McKee et al., 2020), machinery losses, protection costs (Gren et al., 2019), and livestock damages, were incorporated into the analysis.

The economic significance of wild pig management becomes more apparent when contrasted with other major public initiatives in Brazil. For instance, Silva & Ferreira Filho (2018) found that the Family Grant (Bolsa Família – social program for low-income households in Brazil) transfer program contributed to a 0.16% increase in the GDP from 2005 to 2012. Similarly, Gianetti & Ferreira Filho (2024) demonstrated that restoring 19.5 million hectares of degraded pasture could yield a GDP increase of 0.53% to 0.59% between 2020 and 2035. In comparison, managing the wild pig population is projected to contribute to GDP growth of 0.08% to 0.24% between 2023 and 2030, highlighting its considerable economic potential.

These findings are essential to our study, particularly in underscoring the need to educate hunters and the public about the economic and environmental impacts of wild pig proliferation. Raising awareness may help deter behaviors that contribute to the spread of these animals (Grady et al., 2019; McLean et al., 2021). The increase in agricultural production results in higher real household wages and lower food prices, leading to a rise in real household consumption between 0.09% and 0.28%. This increase translates into an average per-household consumption gain ranging from US$115.77 in the minimum scenario to US$151.49 in the intermediate scenario and up to US$184.69 in the maximum scenario.

Furthermore, the heightened output of corn and soybeans, two of Brazil's primary export commodities, bolsters export volumes. Concurrently, GDP growth drives a corresponding increase in imports. While the intensity of GHG emissions at the crop level decreases due to enhanced efficiency in input use, the overall economic expansion is projected to result in a modest rise in total GHG emissions, estimated to be between 0.02% and 0.06% above baseline levels by 2030.

Table 7. Simulation results, macroeconomic factors, GHG emissions, accumulated percentage difference from the 2030 baseline.

Variables	Minimum	Intermediate	Maximum
Real Household Consumption	0.09	0.17	0.28
Real GDP	0.08	0.15	0.24
Exported volume	0.15	0.29	0.45
Imported volume	0.16	0.31	0.49
Real food consumer price index	-0.09	-0.19	-0.31
GHG Emissions	0.02	0.04	0.06

Source: The authors.

The changes in land use resulting from policy shocks are relatively minimal, primarily affecting crop production. Under the minimum and maximum scenarios, crop expansion is anticipated to increase by 0.03 to 0.09 million hectares, respectively (Table 8). This expansion is expected to occur primarily at the expense of pasture areas rather than through the conversion of native

[9] Methodological differences should be considered when making these comparisons.

forests. Consequently, the implementation of wild pig management policies may lead to a land-saving effect, potentially preventing deforestation of between 0.01 and 0.03 million hectares.

The relationship between crop yield and land use change is frequently examined through the perspective of land-saving versus deforestation-inducing outcomes (Hertel, 2012; Hertel et al., 2014). These outcomes are influenced by various factors, including the nature of technological advancements and the specific regional context of yield gains. However, research by Villoria et al. (2014) suggests that most crop yield gains tend to have land-saving effects. Our findings align with this perspective, showing that while productivity-induced crop gains had a limited overall impact on land-use change, they did help alleviate pressure on deforestation.

Furthermore, if damages to livestock, such as sheep, which often represent a primary concern in areas affected by wild pigs (McLean et al., 2021), were considered, the potential increases in pasture productivity could further enhance land-saving benefits. This dynamic has been demonstrated in previous research conducted by Gianetti & Ferreira Filho (2024).

Table 8. Simulation results showing land use changes accumulated from the 2030 baseline (Mha)

LUC	Minimum	Intermediate	Maximum
Crop	0.03	0.05	0.09
Pasture	-0.03	-0.06	-0.09
Planted Forest	-0.01	-0.02	-0.03
Unused	0.01	0.02	0.03

Source: The authors.

4.2. Regional impacts

The rise in corn and soybean production in Brazil's Midwest, South, and Southeast regions, areas most impacted by wild pigs, may result in a decrease in the yield of these crops in the North and Northeast regions (Table 9). The decline in prices, accompanied by a consequent reduction in the rate of return on agricultural activities in those regions, contributes to this downturn. Consequently, the production losses in areas not affected by wild pigs align with the regional disparities identified by Holderieath et al. (2018, 2022).

However, by utilizing a Computable General Equilibrium (CGE) model, we were able to capture the broader economic impacts, including beneficial spillovers resulting from heightened overall economic activity. Consequently, real GDP experiences growth across all Brazilian regions, not solely in areas directly affected by the expansion of crops (Table 10). Thus, managing the wild pig population can simultaneously improve food security by reducing food prices and foster regional development by boosting GDP at the national level.

Previous studies in Brazil, such as those conducted by Lobo (2022), have examined the crop losses caused by wild pigs. The study by Lobo (2022) estimated average crop production losses in 2020 across the Southeast, Midwest, and South regions, with losses ranging from 5.9% to 8.8% for corn, 1.7% to 4.0% for soybeans, and 0.0% to 4.2% for sugarcane. In contrast, our methodology allocates regional crop damage based on the proportion of wild pig harvests reported in each area, providing a different perspective. Our findings indicate that most crop damage is concentrated in the South, particularly in the states of Paraná and Rio Grande do Sul (Table 4), which report the highest percentage of municipalities with wild pig presence (Pedrosa et al., 2015; Hegel et al., 2022). However, the Midwest region is projected to experience the most substantial GDP gains from effective wild pig population management, particularly in the states of Mato Grosso do Sul, Mato Grosso, and Goiás and the Federal District (Table 10), as these areas are reliant on crop production compared to the others.

Table 9. Simulation results for the intermediate scenario, regional crop output, and greenhouse gas (GHG) emission intensity, showing the cumulative percentage difference from the 2030 baseline.

Crops	Corn		Soybeans		Sugarcane	
	Output	Emission Intensity	Output	Emission Intensity	Output	Emission Intensity
Rondonia	-0.99	-0.25	0.03	-0.21	0.32	-0.21
AmazACRR	-0.82	-0.21	0.05	-0.12	0.13	-0.18
ParaAP	-0.90	-0.24	-0.05	-0.18	0.12	-0.11
Bahia	-1.61	-0.32	-0.02	-0.15	0.20	-0.08
MaToPi	-0.66	-0.20	0.10	-0.20	0.29	-0.12
Rnordeste	-1.92	-0.28	-0.07	-0.05	0.24	-0.11
MinasG	30.81	-5.60	20.56	-4.17	0.00	-0.19
SaoPaulo	29.39	-4.41	20.72	-3.88	0.06	-0.13
Rsudeste	-2.28	-0.33	-0.69	-0.27	0.06	-0.08
Parana	5.81	-1.69	4.64	-1.33	0.57	-0.26
Rsul	103.47	-12.07	22.59	-4.52	0.00	-0.26
MtGrSul	14.69	-3.12	15.59	-3.61	0.00	-0.51
MtGrosso	0.76	-0.68	0.54	-0.33	0.00	-0.03
GoiasDF	13.81	-3.11	6.70	-1.96	0.00	-0.25

Source: The authors.

Table 10. Simulation results for the intermediate scenario, regional macroeconomic, and greenhouse gas (GHG) emissions, and the cumulative percentage difference from the 2030 baseline.

Regions	Real GDP	Real Household Consumption	Food Consumer Price Index	GHG Emissions
Rondonia	0.06	-0.08	-0.002	-0.20
AmazACRR	0.01	-0.07	-0.004	-0.41
ParaAP	0.04	-0.04	-0.01	-0.22
Bahia	0.01	-0.09	-0.02	-0.11
MaToPi	0.03	-0.10	-0.01	-0.22
Rnordeste	0.01	0.01	-0.03	0.00
MinasG	0.28	0.39	-0.02	0.14
SaoPaulo	0.04	0.10	-0.06	0.06
Rsudeste	0.01	0.06	-0.02	-0.06
Parana	0.18	0.18	-0.01	0.14
Rsul	0.32	0.56	-0.02	0.31
MtGrSul	1.34	1.12	0.001	0.59
MtGrosso	0.38	-0.33	-0.004	-0.15
GoiasDF	0.44	0.30	-0.01	0.25

Source: The authors.

Managing the wild pig population is likely to result in an overall increase in total GHG emissions in most regions of the Midwest, Southeast, and South of Brazil, primarily driven by heightened economic activity (Table 10). In contrast, the North and Northeast regions (Table 2), where land-saving effects are observed (Table 11), would experience a reduction in GHG emissions due to increased production in other areas in the country. Nevertheless, the GHG emission intensity for corn, soybeans, and sugarcane is expected to decrease across all regions (Table 9). In the South, mainly in the state of Rio Grande do Sul, the area most impacted by wild pig activities, we anticipate a reduction in GHG emission intensity of over 12.5% for corn and 4.5% for soybeans in the intermediate scenario.

Table 11. Simulation results for the intermediate scenario and regional land-use change cumulative from the 2030 baseline (1,000 ha).

Regions	Crop	Pasture	Planted Forest	Unused
Rondonia	-0.26	-0.92	0.00	1.18
AmazACRR	-0.43	-1.09	-0.12	1.63
ParaAP	-0.67	-3.53	-0.29	4.48
Bahia	-0.68	-4.14	-0.09	4.91
MaToPi	-2.14	-4.97	0.01	7.09
Rnordeste	0.00	0.00	0.00	0.00
MinasG	11.65	-9.81	-2.39	0.56
SaoPaulo	2.46	0.00	-2.46	0.00
Rsudeste	0.05	0.00	-0.05	0.00
Parana	2.04	0.00	-2.04	0.00
Rsul	8.52	0.00	-8.52	0.00
MtGrSul	23.89	-20.85	-0.87	-2.16
MtGrosso	-3.35	-0.36	0.01	3.71
GoiasDF	11.47	-11.24	-0.32	0.10

Source: The authors.

In addition to reducing GHG emissions and mitigating land-use changes, managing the wild pig population could enhance other ecosystem services such as soil quality, water availability, and the overall health of fauna and flora. Wild pigs adversely affect vegetation and soil by disrupting plant and animal invertebrate communities, promoting slope erosion, and degrading ecosystem quality (Bratton, 1974; Massei & Genov, 2004; Hegel & Marini, 2013). These environmental impacts have a direct influence on agricultural production. Therefore, preventing damage caused by wild pigs would yield both socioeconomic and environmental benefits.

5. Conclusions

Effectively managing the wild pig population could enhance the production of corn, soybeans, and sugarcane in Brazil, leading to increased overall economic activity, household consumption, and exports. Additionally, this approach would lower agricultural GHG emission intensity and contribute to the prevention of deforestation. Furthermore, it would safeguard the environment by preserving soil and water quality, as well as protecting native fauna and flora.

Estimating the damage caused by wild pigs to crops and understanding their effects on the Brazilian economy, greenhouse gas (GHG) emissions, and land-use changes (LUC) can provide policymakers with essential insights. This analysis facilitates comprehensive cost-benefit assessments of public investments, aids in formulating regional policies to address crop damages, and supplies crucial data for creating more effective insurance coverage for farmers.

To the best of the authors' knowledge, this study is pioneering in providing a general equilibrium assessment of wild pig population management in Brazil. However, it is essential to acknowledge the uncertainties inherent in such studies, particularly those related to population dynamics across various regions of the country. Enhancing surveillance and assessments of wild pig populations, considering Brazil's diverse landscapes and edaphoclimatic conditions, can improve the accuracy of predictions and modeling. These enhancements are crucial for developing more effective policies to manage wild pig populations.

Authors' contributions

GWG: Conceptualization, Formal analysis, Methodology, Software, Writing – original draft. CGZH: Methodology, Writing – review & editing. JBSFF: Methodology, Software, Validation, Writing – review & editing.

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Research data is available upon request. Wild pig management data should be requested to the Brazilian government.

*Corresponding author:

Giovani William Gianetti. Giovani.gianetti@gmail.com

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