Wild pigs (*Sus scrofa*) population management in Brazil: mitigating crop damages

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Abstract

This paper evaluates wild pig management in Brazil by systematically assessing the avoided crop damage impacts of controlling the wild pig population and their repercussions on both economic and environmental aspects. We employed the Computable General Equilibrium model TERM-BR15 to conduct simulations from 2023 to 2030. We developed three scenarios, varying in the intensity of wild pig damage, ranging from minimum to maximum. Within these scenarios, we introduced shocks of increasing corn, soybeans, and sugarcane outputs by adjusting the pig harvest rate (HR) from 25% to 50% and modifying crop consumption (CC) based on the animals' body weight, ranging from 3% to 5%. The intermediate scenario shows a 0.15% increase in Gross Domestic Product and a 0.17% rise in real household consumption compared to the 2030 baseline, attributed to wild pig population management measures. These figures represent increments of US$ 203.18 and US$ 151.49 per wild pig managed, respectively (based on a BRL to US$ exchange rate of 5). National output for corn, soybeans, and sugarcane would increase by 11.10%, 6.33%, and 0.08%, respectively, alongside a reduction in greenhouse gas (GHG) emissions intensity and a reduction in deforestation. Regionally, real GDP would increase in all Brazilian regions. However, areas unaffected by wild pigs would experience a decrease in grain production due to declining prices resulting from increased output in other regions. Our results offer an evidence-based estimation of wild pig crop damages and their impact on the Brazilian economy and environment. This information can assist decision-makers in actively shaping public policies for wild pig population management.

Keywords: Wildlife management, Wild boar, Feral hogs, Pest control, Computable General Equilibrium.

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1. Introduction

The wild pig (*Sus scrofa*) is a native species from Eurasia and North Africa. However, it has been introduced globally for commercial and hunting purposes (West et al., 2009; Hegel et al., 2022). This species demonstrates resilience and adaptability to diverse edaphoclimatic conditions (Baskin and Danell 2003). This adaptability is facilitated by its prolific reproduction, omnivorous diet, and a low presence of predators, particularly in non-native habitats (Barrios-Garcia & Ballari, 2012).

The behavioral traits of wild pigs, ranging from rooting to wallowing, exert multifaceted impacts on the fauna and flora. These behaviors can alter soil physical, biological, and chemical properties, as well as impact water quality and vegetation cover (Massei & Genov, 2004). Additionally, they influence fauna population dynamics, habitat integrity, and nesting opportunities (Ickes et al., 2005; Barrios-Garcia & Ballari, 2012). Wild pigs pose challenges to native species by competing with them and potentially aiding in the spread of diseases (Hegel et al., 2019b). Furthermore, the wild pig benefits from abundant food sources due to agricultural expansion. Its consumption of crops and husbandry directly affect farmer profitability and productivity, consequently heightening the necessity for species management.

Managing the wild pig population presents substantial challenges for Brazil, a global leader in the production of various commodities, including soybeans, corn, cotton, orange juice, poultry, and beef. From 2011 to 2020, Brazil experienced an annual increase of 3.1% in agricultural production. During this period, its agricultural Total Factor Productivity exhibited a growth rate of 2.0% annually, nearly twice the global average of 1.1% (OECD, 2023). Similar to the agricultural production, wild pig population in Brazil has increased over the years (Hegel et al., 2022), being recognized as a pest. The Brazilian wildlife department (Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis - IBAMA) declared it an invasive and dangerous species in 2013 (Brazil, 2013). As a measure of population control, authorized hunters[4] registered at IBAMA are permitted to manage the wild pig population without specific quotas or seasonal restrictions (Brazil, 2023a).

From 2020 onwards, we observed an increase in registered hunters with IBAMA, soaring from 24,611 in 2020 to 61,015 by 2022. The recorded harvest of wild pigs surged as well, escalating from approximately 78,718 in 2020 to 153,430 in 2022, marking a 97.4% growth (Brazil, 2023b)[5].

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

[5] Personal information request to IBAMA.

However, a shift in government policies in 2023 resulted in a temporary ban on firearm-based harvesting from July to December that year (Brazil, 2023c). This action may lead to a spike in wild pig population, potentially escalating the damage to crop production and the environment. This demonstrates the dependence of wild pig population control on regulatory changes, executive orders, and laws, all subject to fluctuating levels of restriction or leniency.

Previous studies in Brazil focused on evaluating harvesting practices (Rosa et al., 2018; Carvalho et al., 2019;). These studies examined various aspects, including the average wild pigs harvested, motivations driving control efforts, and the legal framework of harvesting activities. Pedrosa et al. (2015) and Hegel et al. (2019a, 2022) and delved into analyzing population dynamics and behavior patterns of wild pigs, such as habitat preferences, and the spatial distribution of wild pig dispersion. Furthermore, Cervo & Guadagnin (2020) and Pedrosa et al. (2021) conducted studies focused on the dietary habits of wild pigs in Brazil. Their findings revealed that over 90% of the wild pig diet consists of vegetal matter, with agricultural crops contributing to at least 40% of their diet, excluding the Pantanal biome.

Studies on wild pigs in Brazil have not provided a comprehensive overview of population density, such as Bieber & Ruf (2005), which encompass asymptotic growth rates under diverse environmental and biological conditions. Remarkably, there is currently no data about the estimated wild pig population in Brazil. Additionally, assessments considering crop damages, and their integrated socioeconomic effects, as explored by Holderieath et al. (2022) and Anderson et al. (2016), remain scarce in the Brazilian context. Among the available studies, Lobo (2022) encompasses estimations of harvest efforts, crop damage assessments survey, and the simulation of economic damages caused by wild pigs in a hypothetic scenario.

In this paper we introduced three population management scenarios and their direct effects on crop damage into a novel approach for analyzing the wild pig hazard through economic modeling in Brazil. The different degrees of crop damage impact agricultural product markets and land productivity. These effects have far-reaching implications, potentially affecting primary factor usage, land use patterns, economic growth, household welfare, and greenhouse gas emissions. The analysis was performed through a Computable General Equilibrium model, considering the period spanning 2023 to 2030. This paper contributes to the literature on wild pig management in Brazil by systematically assessing the avoided crop damage impacts of curbing wild pig population and their repercussions on both economic and environmental aspects.

2. Methodology

We used a computable, dynamic, inter-regional and bottom-up general equilibrium model, called The Enormous Regional Model for Brazilian Economy (TERM-BR), simulating scenarios for the period 2023 to 2030. The TERM-BR15 is calibrated for 2015, and updated throughout historical simulation to 2022, based on Gianetti and Ferreira Filho (2024).

The model also presents two modules of GHG emissions, one linked to fuel and other emissions in productive activities; and the other related to land use, land use change, and forestry (LULUCF), accounting for greenhouse gases (GHG) emissions from land use transitions, the available land stock, and the deforestation rate, for 4 broad land use categories (Agriculture, Pastures, Planted Forests, Unused[6]), 6 Brazilian biomes and 27 regions representing the 26 states and the Federal District. To minimize computational effort and the complexity of analysis, the original 27 regions were aggregated into 15 regions as outlined in Table 1.

Table 1. TERM-BR15 aggregation of the Brazilian states

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

Source: Gianetti and Ferreira Filho (2024).

2.1. Simulation Strategy

We employed a simulation strategy with a three-step process to construct baseline scenarios from 2023 to 2030. First, we simulated the historical behavior of the economy, from the model's base year of 2015 to 2023, utilizing observed macroeconomic data of Gianetti and Ferreira Filho (2024). Subsequently, we projected the business-as-usual (BAU) trajectory of the economy for the period from 2023 to 2030, using macroeconomic projections of Gianetti and Ferreira Filho (2024). This

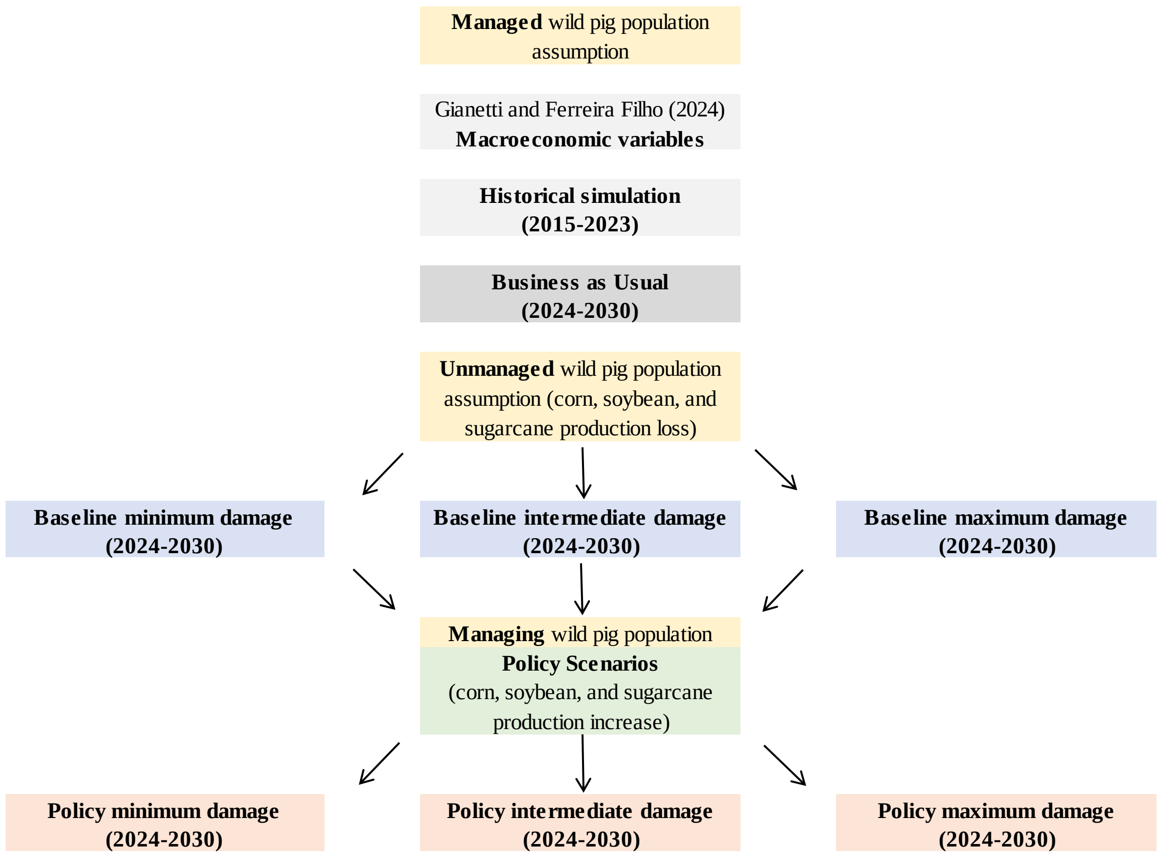
[6] Includes native vegetation, rivers, roads, and other land not used for agriculture.

simulation was built under the assumption that strategies for controlling the wild pig population were integrated into the macroeconomic, agricultural productivity, and land use change projections for the country, as wild pig harvesting was allowed in TERM-BR base year of 2015.

The third step implemented crop damage shocks to corn, soybean, and sugarcane production, as result of different growth projections for the wild pig population from 2023 to 2030, contrasting scenarios with unmanaged populations against those with managed populations under three distinct levels of damage intensity. Consequently, this approach resulted in three separate baseline projections for the Brazilian economy in 2030, each assuming different wild pig population in unmanaged circumstances.

We then estimated policy scenarios with shocks to increase corn, soybean, and sugarcane production, considering management of the wild pig population under three levels of intensity. This strategy enabled us to show the economic benefits of managing the wild pig population, rather than the economic losses incurred from neglecting management efforts. That is the reason why it was necessary to initially simulate a BAU scenario that allowed crop production to be endogenously determined. This served as a foundation for comparing the baseline impacts of an unmanaged wild pig population against policy scenarios that highlight the benefits of population control.

Figure 1. Simulation strategy



Source: authors.

2.2. Baseline simulations

We only simulated crop damage in some regions: Brazil's mid-west, southeast, and south regions[7]. We gathered the 2022 population projection for wild pigs at a regional level from observed population management data, assuming harvest rates of 25%, 33%, and 50% of total population. Those are based on female wild pig mortality rate (informed in IBAMA reports), which is the key determinant to population dynamics (see in Hegel, 2021). To estimate the difference in populations between managed and unmanaged projections, we adopted annual asymptotic growth rates of 9% and 63% respectively, based on research by Bieber & Ruf (2005). While the population growth rate may appear high, alternative studies such as Gren et al. (2016) have estimated an average intrinsic growth rate for the wild pig population in Sweden to be 48% between 2004 and 2011.

We estimated crop damage on corn, sugarcane, and soybeans analyzing wild pig diet, drawing from studies such as Pedrosa et al. (2021) for corn and sugarcane and Cervo & Guadagnin (2020) for soybeans. Corn accounted for approximately 61.7% of wild pig diet over a span of 4 months annually, while soybeans and sugarcane[8] represented 45%[9] and 15.8% of the wild pigs' diet during the same period, respectively. Our calculations factored in a daily consumption range of 3% to 5% of the animal's body weight (Bodenchuk, 2008), along with mean body weights obtained from harvested wild pig data as per Brazil (2023b). Utilizing this data, we assessed the crop damage caused by the unmanaged wild pig population relative to the BAU simulation. This strategy aligns with the findings of Gren et al. (2019b), which indicate that the presence of wild pigs is positively correlated with damage.

Therefore, we simulated three baseline scenarios (Table 2). We estimated the baseline shocks from the projected annual wild pigs increase ranging from 1,925.1 to 3,850.2 thousand animals in the unmanaged projection compared to the managed. This surge corresponds to crop damages ranging from 596.9 to 1,989.6 thousand tons (Table *2*).

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

[8] Specifically applied to Paraná and São Paulo, regions where wild boar damages to sugarcane crops are more prevalent.

[9] Cervo & Guadagnin (2020) reported that the volume of food found in the stomachs of wild pigs consisted of 44.4% cultivated grain in the Araucaria Forest and 48.1% in the Pampa vegetations. Considering that soybeans represent the largest first crop culture in Brazil, covering over 41 million hectares and constituting 48% of the annual crop cultivated area, we approximated the mean wild pig diet to be 45% soybeans in one third of the year.

Table 2. 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% 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% 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% 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: authors.

2.3. Policy Shocks

To assess the impacts of wild pig management, we then implemented policy shocks of the increase in corn, soybeans, and sugarcane crops implementing wild pig population control measures from 2023 to 2030, as depicted in Table 3, showing the final policy shocks.

Table 3. 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		3.91	2.71		6.72	4.59	
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		10.68	2.95		19.97	5.02	
MtGrSul	0.96	1.02		1.98	2.09		3.33	3.52	
MtGrosso	0.05	0.04		0.11	0.08		0.18	0.13	
GoiasDF	0.91	0.46		1.86	0.93		3.13	1.55	
Brazil	0.77	0.44	0.01	1.52	0.88	0.01	2.43	1.44	0.02

Source: authors.

The regional distribution of shock was determined by estimating the wild pig population and crop output. The estimates of the wild pig population were derived from the percentage of animals harvested in 2023 (Table 4), the most recent data available from Brazil (2023b). Crop output was calibrated using the TERM-BR15 model and simulations. Consequently, the relationship between crop damage size and crop output determined the size of the shocks. Regions with a higher percentage of wild pig harvest, such as Rsul with 28.60%, experienced greater production increase shocks. The Southern region of Brazil was officially the first to record the dispersion of wild pigs in the late 1980s, although unofficial records exist dating back to the 1960s (Deberdt & Scherer, 2007; Salvador, 2012).

Nonetheless, regions like MtGrosso with only 3.11% of animals harvested, faced lower impacts. Despite MtGrosso being Brazil's largest grain producer and potentially facing an expansion of wild pigs without population management, we maintained the shock estimation based on the region's initial share of wild pig harvest.

Table 4. 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: authors. Data from Brazil (2023b).

3. Results

Managing the wild pig population in Brazil would lead to a production increase of corn, soybeans, and sugarcane, subsequently reducing the GHG emission intensity (emissions per unit of output) associated with these crops (Table 5). The impact is larger for corn, given its higher consumption share in wild pigs' diet, with output increases ranging from 5.49% and 18.33%, accompanied by a decrease in emissions intensity between 1.56% and 4.97%, from the minimum to maximum scenarios relative to the 2030 baseline, respectively. Soybeans production would rise between 3.12% and 10.52%, coupled with emissions intensity reductions from 0.85% to 2.72%. Sugarcane output would increase between 0.04% and 0.15%, with corresponding emissions intensity reductions from 0.09% to 0.29%. Notice that we did not incorporate the consumption of other crops, husbandry, pasture, and roots due to insufficient data. Consequently, the overall damage could potentially be even higher than estimated.

Table 5. Simulation results, crops output and 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: authors.

Increasing crop production leads to a surge in economic activity, reflecting a difference in real GDP growth ranging from 0.08% to 0.24% in the three scenarios for 2030, relative to the baseline, as outlined in Table 6. This rise in production corresponds to an increase in real household wages and a reduction in food prices, fostering a growth in real household consumption between 0.09% and 0.28%.

Notably, the heightened production of corn and soybeans, key exports for Brazil, bolsters the country's export volumes. The GDP growth also induce an increase in imports. Despite the reduction in GHG emission intensity in crops, the overall economic growth contributes to a marginal rise in total GHG emissions, estimated between 0.02% and 0.06% accumulated by 2030 relative to the baseline.

Table 6. Simulation results, macroeconomic and 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
GHG Emissions	0.02	0.04	0.06

Source: authors.

Land use changes resulting from the policy shocks are minimal due to the concentrated impacts on crops. The expansion of crops would potentially increase its area by 0.03 to 0.09 million hectares in the minimum and maximum scenarios, respectively (Table 7). This expansion would occur mostly at the expense of reductions in pasture areas. Thus, crop expansion would have a land-saving impact, preventing deforestation in native forests in Brazil, estimated between 0.01 and 0.03 million hectares.

Table 7. Simulation results, land use change 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: authors.

Contradictorily, the increase in corn and soybean production in the mid-west, south, and southeast regions – areas affected by wild pigs – could result in a decrease in the output of these crops in the north and northeast regions (Table 8). This decline is due to the ensuing lower prices and a reduction in the rate of return on activities in these regions. However, despite this regional curb in crop output, GDP would increase across all regions in Brazil (Table 9) due to positive indirect effects to other industries.

Table 8. Simulation results intermediate scenario, regional crops output and GHG emission intensity accumulated percentage difference from the 2030 baseline

Crops	Corn		Soybeans		Sugarcane	
	Output	Emissions Intensity	Output	Emissions Intensity	Output	Emissions 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: authors.

Table 9. Simulation results intermediate scenario, regional macroeconomic and GHG emissions accumulated percentage difference from the 2030 baseline

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

Source: authors.

In the north and northeast regions (Table 1), where we observed land-saving effects (Table 10), GHG emissions would decrease due to increased production in other parts of Brazil (Table 9). The GHG emission intensity of corn, soybeans, and sugarcane would reduce across all regions in the country (Table 8). However, the management of the wild pig population, while boosting economic activity, would lead to an overall increase in total GHG emissions in most of the mid-west, southeast, and south Brazilian regions.

Table 10. Simulation results intermediate scenario, regional land use change accumulated 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: authors.

4. Discussion

4.1. Socioeconomic impacts

Our scenarios outlined the potential economic growth for Brazil resulting from wild pig management. In terms of monetary value, GDP growth from wild pig management would range from increases of US$ 2.1 to US$ 6.7 billion (based on a BRL to US$ exchange rate of 5) in the minimum and maximum crop damage scenarios, respectively. These figures represent the net average GDP benefits of US$ 155.94, US$ 203.18, and US$ 246.44 per wild pig harvested, in the minimum, intermediate, and maximum scenario, respectively. It would also result in average household consumption increase of US$ 115.77, US$ 151.49, and US$ 184.69, respectively. Compared with the total areas dedicated to corn, soybeans, and sugarcane cultivation in Brazil's regions affected by wild pigs, this would represent an average annual GDP increase ranging from a minimum of US$ 5.50 per hectare to US$ 10.84 in the intermediate scenario and US$ 17.35 in the maximum scenario.

Relatively to the economy size, managing the wild pig population could potentially yield impacts ranging from 0.08% to 0.24% between 2023 and 2030. Silva and Ferreira-Filho (2018) regarding the 'Bolsa Família Program,' Brazil's income transfer public program, showed that if the program were funded through government debt, it would contribute to a GDP growth of 0.16% between 2005 and 2012. This comparison highlights the monetary importance of wild pig population management for Brazil.

Previous studies conducted in Brazil, such as those by Pereira et al. (2019) and Lobo (2022), have also examined wild pig damages. Pereira et al. (2019) reported crop damages ranging from US$ 500.00 to US$ 3,000.00. Unfortunately, within the framework of the TERM-BR model, providing individual farmer losses is not feasible due to the economic structure of the model. Additionally, the model operates at a regional level, aggregating damage, which is not expected to be uniformly distributed across farms.

While Lobo (2022) estimated crop damages in 2020 for the Southeast, Midwest, and South Brazilian regions between 5.9% and 8.8% for corn; from 1.7% to 4.0% for soybeans; and from 0.0% to 4.2% for sugarcane. Our approach to regional crop damage distribution, based on the percentage of wild pig harvest in each region, presents a different perspective. According to our analysis, most of the damage would be concentrated in the South of Brazil, particularly in Paraná and Rsul (refer to Table *3*). These regions have the largest share of municipalities that have reported the presence of wild pigs (Pedrosa et al., 2015; Hegel et al., 2022). Nevertheless, the Mid-West region would experience higher GDP growth with wild pig management, particularly in MtGrSul, MtGrosso, and GoiasDF (refer to Table 9), as their regional output is more reliant on crop production compared to the Southern regions.

Regions such as Rondonia, AmazACRR, ParaAP, Bahia, MaToPi, Rnordeste, and Rsudeste would experience lower crop production due to increased output in other regions (refer to Table 8), which causes lower prices and thus reduces the rate of return on agricultural activities in these aforementioned regions. The losses in regions unaffected by wild pigs are comparable to those reported by Holderieath et al. (2018, 2022). However, since we employed a general equilibrium model, we were able to capture the additional benefits from increased economic activity, leading to a greater GDP across all Brazilian regions (Refer to Table 9 for details). Hence, managing the wild pig population could contribute to enhancing food security by ensuring lower food prices. Additionally, it could foster regional development by bolstering GDP across all of Brazil.

Our study, incorporating general equilibrium effects, has recorded GDP losses in Brazil ranging from approximately US$ 300 million to over US$ 950 million per year. These figures surpass those presented in previously mentioned by Anderson et al. (2016), Gren et al. (2019b), Holderieath et al. (2018, 2022), Lobo (2022), McKee et al. (2020), Pereira et al. (2019), Poudyal et al. (2017), and Tian et al. (2023). However, direct comparison is hindered by differences in farmland size, wild pig population dynamics, and total affected area. Furthermore, McKee et al. (2020) underscore that the potential for even greater damages in Brazil when considering impacts on 'second-tier' crops. While Gren et al. (2019) have included damages to machinery and protection costs. We did not explore these variables in our model. Additionally, losses in forestland and pastureland productions were not considered, which may further increase the damages caused by wild pigs in Brazil.

4.2. Environmental impacts

Avoiding crop losses associated with wild pig population management would be associated with lower GHG emissions intensity in crop production and avoided deforestation. Therefore, preventing wild pig damage would be socioeconomic and environmentally beneficial. Furthermore, other ecosystemic services could improve as well, enabling better soil, water, fauna and flora conditions. The impact on vegetation and soil caused by wild pig's changes plant and animal invertebrate communities, facilitates erosion of slopes, and alters the ecosystem quality (Bratton, 1974; Massei and Genov, 2004; Hegel and Marini, 2013), and this directly implies in agricultural production.

Avoiding output losses resulting from wild pig damages would lead to an average increase in corn, soybean, and sugarcane productivity, which is an increase in the output-inputs relationship. The productivity gains are reflected in lower GHG emissions per unit of output (emissions intensity), as demonstrated in Table 5 and Table 8. For instance, regionally, in Rsul, which is the most affected by wild pig activities, in the intermediate scenario a reduction in GHG emissions intensity of more than 12.5% for corn and 4.5% for soybeans would be observed. This impact underscores how managing the wild pig population could contribute to Brazil's progress towards achieving its Sustainable Development Goals and meeting its commitments under the Paris Agreement for reducing GHG emissions (Brazil, 2022).

Gianetti and Ferreira Filho (2024) presented the potential impact of enhancing agricultural productivity on GHG emissions intensity. Their research suggests that increasing beef and dairy cattle production by approximately 1.6% annually could lead to a decrease in GHG emissions intensity by 22.4% for beef and 9.8% for dairy cattle. These findings agree with our, where we observed that mitigating wild pig damage could contribute to reducing GHG emission intensity. Nevertheless, the overall growth in economic activity may still lead to an increase in total GHG emissions. However, our research did not take into account the GHG emissions from the wild pig population, which could be mitigated through the population management.

The impact of changes in agricultural productivity on land-use change is often assessed through discussions of land-saving or increases in deforestation rates (Hertel, 2012; Hertel et al., 2014). While these outcomes depend on various factors such as the characteristics of technological advancements and the regional scope of productivity increases, studies such as that by Villoria et al. (2014) suggest that most assessments of increases in land productivity show land-saving effects.

Our findings are in line with this perspective. Although changes in crop productivity have shown limited impacts on land-use change, they could potentially prevent deforestation on a scale of 10,000 to 30,000 hectares from 2023 to 2030. However, if damages to livestock were also considered, enhancing pasture productivity could yield even greater impacts, as illustrated by Gianetti and Ferreira Filho (2024).

5. Conclusion and policy implication

Managing the wild pig population has the potential to increase corn, soybean, and sugarcane output, thereby elevating the overall economic activity level, household consumption, and exports in Brazil. Simultaneously, it would effectively reduce agricultural GHG emission intensity and prevent deforestation. Furthermore, this management could prevent environmental damage to soil and water quality, as well as protect native fauna and flora. However, the current CGE model does not measure these specific environmental impacts, which we believe is important to investigate in the future.

Providing an estimation of wild pig crop damages and its impact on the Brazilian economy, GHG emissions, and land use change (LUC) can aid decision-makers in actively and precisely shaping public policies for population control management. This enables a comprehensive cost-benefit analysis of public investments and socioeconomic returns, facilitates the formulation of regional policies to compensate for crop damages, and offers valuable data for designing more effective insurance coverage for farmers.

To the best of the authors' knowledge, this study represents the first general equilibrium assessment of wild pig population management in Brazil. Nonetheless, we should stress the uncertainties inherent in studies of this kind, especially those related to population dynamics across the Brazilian regions. Improving surveillance and assessments of wild pig populations, taking into account the diverse landscapes and edaphoclimatic conditions in Brazil, would enhance our ability to predict and model their impacts more accurately. Such improvements are essential for formulating more effective policies to address this issue. Consequently, comprehensive, and wide-ranging studies on wild pigs in Brazil are important to developing strategies to manage this population more effectively.

Bibliographic references

Anderson, A., Slootmaker, C., Harper, E., Holderieath, J., & Shwiff, S. A. (2016). Economic estimates of feral swine damage and control in 11 US states. *Crop Protection*, *89*, 89–94. https://doi.org/10.1016/j.cropro.2016.06.023

Barrios-Garcia, M. N., & Ballari, S. A. (2012). Impact of wild boar (Sus scrofa) in its introduced and native range: a review. *Biological Invasions*, *14*(11), 2283–2300. https://doi.org/10.1007/s10530-012-0229-6

Baskin, L.M., & Danell, K. 2003. Ecology of ungulates: A handbook of species in Eastern Europe and Northern and Central Asia. Berlin: Springer

Bieber, C., & Ruf, T. (2005). Population dynamics in wild boar *Sus scrofa*: ecology, elasticity of growth rate and implications for the management of pulsed resource consumers. *Journal of Applied Ecology*, *42*(6), 1203–1213. https://doi.org/10.1111/j.1365-2664.2005.01094.x

Bodenchuk, M. J. (2008). *Feral Hog Management: Typing Performance Measures to Resources Protected*. https://digitalcommons.unl.edu/feralhoghttps://digitalcommons.unl.edu/feralhog/8

Bratton, S. 1974. The effect of the European wild boar (*Sus scrofa*) on the high-elevation ver-nal flora in Great Smoky Mountains National Park. Bulletin of the Torrey Botanical Club, 101:198-206. http://dx.doi.org/10.2307/2484644

Brasil. (2022). *Brazil's Nationally Determined Contributions*. https://unfccc.int/NDCREG

Brazil. (2013). INSTRUÇÃO NORMATIVA Nº 03/2013, de 31 de janeiro de 2013. In *INSTITUTO BRASILEIRO DO MEIO AMBIENTE E DOS RECURSOS NATURAIS RENOVÁVEIS*. https://www.gov.br/ibama/pt-br/assuntos/biodiversidade/especies-exoticas-invasoras/arquivos/javali/2013_ibama_in_003-2013_manejo_javali.pdf

Brazil. (2023a). DECRETO Nº 11.615, DE 21 DE JULHO DE 2023. In *Presidência da República, Casa Civil*. https://www.planalto.gov.br/ccivil_03/_ato2023-2026/2023/decreto/d11615.htm

Brazil. (2023b). *Fala.BR - Plataforma Integrada de Ouvidoria e Acesso à Informação*. https://falabr.cgu.gov.br/web/home

Brazil. (2023c). *Sistema de Informação de Manejo de Fauna*. IBAMA. https://simaf.ibama.gov.br/index.php

Carvalho, W. D., Mustin, K., Paulino, J. S., Adania, C. H., & Rosalino, L. M. (2019). Recreational hunting and the use of non-selective traps for population control of feral pigs in Brazil. *Biodiversity and Conservation*, *28*(11), 3045–3050. https://doi.org/10.1007/s10531-019-01800-0

Cervo, I. B., & Guadagnin, D. L. (2020). Wild boar diet and its implications on agriculture and biodiversity in Brazilian forest–grassland ecoregions. *Animal Biodiversity and Conservation*, 123–136. https://doi.org/10.32800/abc.2020.43.0123

Deberdt, A. J., & Scherer, S. B. (2007). O javali asselvajado: ocorrência e manejo da espécie no Brasil. *Natureza & Conservação*, *5*(2), 31–44.

Gianetti, G. W., & Ferreira Filho, J. B. de S. (2024). Pasture recovery, emissions, and the Brazilian Paris agreement commitments. *Land Use Policy, 141, 107118.* https://doi.org/10.1016/j.landusepol.2024.107118

Gren, I.-M., Andersson, H., Mensah, J., & Pettersson, T. (2019a). Cost of wild boar to farmers in Sweden. *European Review of Agricultural Economics*. https://doi.org/10.1093/erae/jbz016

Gren, I.-M., Andersson, H., Mensah, J., & Pettersson, T. (2019b). Cost of wild boar to farmers in Sweden. *European Review of Agricultural Economics*. https://doi.org/10.1093/erae/jbz016

Gren, I.-M., Häggmark-Svensson, T., Andersson, H., Jansson, G., & Jägerbrand, A. (2016). Using traffic data to estimate wildlife populations. *Journal of Bioeconomics*, *18*(1), 17–31. https://doi.org/10.1007/s10818-015-9209-0

Hegel, C. G. Z. (2021). *História da invasão do javali (Sus scrofa L.) no Brasil contada pela dispersão e morfologia, com cenários de manejo da espécie* [Universidade de Brasília]. http://repositorio2.unb.br/jspui/handle/10482/43002

Hegel, C. G. Z., Faria, G. M. M., Ribeiro, B., Salvador, C. H., Rosa, C., Pedrosa, F., Batista, G., Sales, L. P., Wallau, M., Fornel, R., & Aguiar, L. M. S. (2022). Invasion and spatial distribution of wild pigs (Sus scrofa L.) in Brazil. *Biological Invasions*, *24*(12), 3681–3692. https://doi.org/10.1007/s10530-022-02872-w

Hegel C.G.Z., Santos L.R., Pichorim M., Marini M.Â. (2019a). Wild pig (Sus scrofa L.) occupancy patterns in the Brazilian Atlantic forest. *Biota Neotropica, 19: e20180719.*

Hegel, C. G. Z., Santos, L. R., Marinho, J. R., & Marini, M. Â. (2019b). Is the wild pig the real "big bad wolf"? Negative effects of wild pig on Atlantic Forest mammals. *Biological Invasions*, *21*(12), 3561–3574. https://doi.org/10.1007/s10530-019-02068-9

Hertel, T. W. (2012). Implications of Agricultural Productivity for Global Cropland Use and GHG Emissions: Borlaug vs. Jevons. *GTAP Working Paper*, *69*, 1–36. https://www.gtap.agecon.purdue.edu/resources/download/6110.pdf

Hertel, T. W., Ramankutty, N., & Baldos, U. L. C. (2014). Global market integration increases likelihood that a future African Green Revolution could increase crop land use and CO2emissions. *Proceedings of the National Academy of Sciences of the United States of America*, *111*(38), 13799–13804. https://doi.org/10.1073/PNAS.1403543111/-/DCSUPPLEMENTAL/PNAS.201403543SI.PDF

Holderieath, J. J., Crosby, M. K., & McConnell, T. E. (2022). Potential welfare impacts from the continued spread of wild pigs. *Q Open*, *2*(2). https://doi.org/10.1093/qopen/qoac027

Holderieath, J. J., Pendell, D. L., Hadrich, J. C., Anderson, A., Slootmaker, C., Harper, E., & Shwiff, S. A. (2018). Valuing the absence of feral swine in the United States: A partial equilibrium approach. *Crop Protection*, *112*, 63–66. https://doi.org/10.1016/j.cropro.2018.05.004

Ickes, K., Paciorek, C.J., Thomas, S.C. (2005). Impacts of nest construction by native pigs (Sus scrofa) on lowland Malaysian rain forest saplings. *Ecology 86:1540-1547.*

Lobo, G. D. (2022). *O javali (Sus Scrofa) no Brasil: controle, prevenção e impactos econômicos* [Universidade de São Paulo]. https://doi.org/10.11606/T.11.2022.tde-09062022-161841

Martins, Fernando. I., Mourão, G., Campos, Z., Pellegrin, A., & Silva, V. S. (2019). ACTIVITY PATTERN AND HABITAT SELECTION BY INVASIVE WILD BOARS (SUS SCROFA) IN

BRAZILIAN AGROECOSYSTEMS. *Mastozoología Neotropical*, *26*(1), 129–141. https://doi.org/10.31687/saremMN.19.26.1.0.08

Massei, G., Genov, P.V. (2004). The environmental impact of wild boar. Galemys, 16(Spe-cial edition):135-145.

McKee, S., Anderson, A., Carlisle, K., & Shwiff, S. A. (2020). Economic estimates of invasive wild pig damage to crops in 12 US states. *Crop Protection*, *132*, 105105. https://doi.org/10.1016/j.cropro.2020.105105

Organization for Economic Cooperation and Development. (2023). *Agricultural Policy Monitoring and Evaluation 2023*. OECD. https://doi.org/10.1787/b14de474-en

Pedrosa, F., Bercê, W., Costa, V. E., Levi, T., & Galetti, M. (2021). Diet of invasive wild pigs in a landscape dominated by sugar cane plantations. *Journal of Mammalogy*, *102*(5), 1309–1317. https://doi.org/10.1093/jmammal/gyab100

Pedrosa, F., Salerno, R., Padilha, F. V. B., & Galetti, M. (2015). Current distribution of invasive feral pigs in Brazil: economic impacts and ecological uncertainty. *Natureza & Conservação*, *13*(1), 84–87. https://doi.org/10.1016/j.ncon.2015.04.005

Pereira, C. Z., Rosa, C., & da Silva Zanzini, A. C. (2019). Perception of presence, impact and control of the invasive species Sus scrofa in the local community living near the Itatiaia National Park, Brazil. *Ethnobiology and Conservation*. https://doi.org/10.15451/ec2019-06-8.06-1-11

Poudyal, N. C., Caplenor, C., Joshi, O., Maldonado, C., Muller, L. I., & Yoest, C. (2017). Characterizing the Economic Value and Impacts of Wild Pig Damage on a Rural Economy. *Human Dimensions of Wildlife*, *22*(6), 538–549. https://doi.org/10.1080/10871209.2017.1368103

Rosa, C. A. Da, Wallau, M. O., & Pedrosa, F. (2018). Hunting as the main technique used to control wild pigs in Brazil. *Wildlife Society Bulletin*, *42*(1), 111–118. https://doi.org/10.1002/wsb.851

Salvador, C. H. (2012). *Ecologia e manejo de javali (Sus scrofa L.) na América do Sul*. Universidade Federal do Rio de Janeiro.

Silva, D. I., & Ferreira-Filho, J. B. de S. (2018). IMPACTOS DOS PROGRAMAS DE TRANSFERÊNCIA DE RENDA BENEFÍCIO DE PRESTAÇÃO CONTINUADA E BOLSA FAMÍLIA SOBRE A ECONOMIA BRASILEIRA: UMA ANÁLISE DE EQUILÍBRIO GERAL. *Pesquisa e Planejamento Econômico* , *48*(1), 161–183.

Tian, N., Gan, J., & Holley, G. (2023). Assessing feral swine damage in the western gulf region of Arkansas, Louisiana, and Texas. *Biological Invasions*, *25*(5), 1527–1540. https://doi.org/10.1007/s10530-022-02994-1

Villoria, N. B., Byerlee, D., & Stevenson, J. (2014). The Effects of Agricultural Technological Progress on Deforestation: What Do We Really Know? *Applied Economic Perspectives and Policy*, *36*(2), 211–237. https://doi.org/10.1093/AEPP/PPU005

Zimmermann, N. P., Peres, I. A. H. F. S., Braz, P. H., Juliano, R. S., Mathias, L. A., & Pellegrin, A. O. (2018). Prevalência sorológica de Brucella spp. em porcos ferais e bovinos em simpatria no Pantanal do Mato Grosso do Sul, Brasil. *Semina: Ciências Agrárias*, *39*(6), 2437. https://doi.org/10.5433/1679-0359.2018v39n6p2437