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The impact of agricultural credit on the cattle inventory and deforestation in Colombia: a spatial analysis

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The relationship between agricultural credit and agricultural production as well as the impacts on sustainable development (i.e., poverty alleviation, reduction of inequalities, food and nutrition security, and stimulation of economic growth) have been widely documented. The objective of this study is to analyze the impact of credit on cattle production and deforestation in Colombia through spatial panel data models. For this purpose, a departmental data panel for the period 2011–2020 was built, based on available information from public entities. The results suggest that in Colombia, the relationship between access to credit and cattle production is significant and can be either negative or positive. In addition, there is evidence of spatial dependence, meaning that cattle production in one department is being affected by cattle production in a neighboring department or by all the departments that make up the national territory. Regarding deforestation, results show that, although the number of cattle present in a department does affect its annual deforestation rate due to a poor coverage of sustainably intensified cattle ranching systems, there is no relationship between deforestation and the access to credit nor any spatial correlations.

The importance of credit for the development of agricultural activities in developing countries has been widely documented[1–8]. In general, these studies show a positive relationship between credit and production, however, an important share of the research describes the ambiguous effects of credit in terms of poverty reduction and welfare improvements of the rural population[6,9,10]. Credits are financing instruments for development since their objective is not only to increase production and productivity, but also to alleviate poverty[11–14]. In this sense, studying the impacts of agricultural credit generates value since it corresponds directly and indirectly to several of the United Nations Sustainable Development Goals (SDG), such as No Poverty (UN-SDG 1), Reduced Inequalities (UN-SDG 10), and Decent Work and Economic Growth (UN-SDG 8)[15]. Formal credit is only one among several instruments to boost the rural and agricultural sector[14,16–19]. Most formal credits involve high transaction costs, information asymmetries, high interest rates, and numerous formal requirements (e.g., collateral). This highlights the importance of the geographical location of financial institutions, the promotion of financial instruments by national and local governments, producer associations, and other stakeholders along the cattle value chains, and the diversification of channels to guarantee financial inclusion[20–23].

In Colombia, agricultural credits are granted through the Fund for the Financing of the Agricultural Sector (FINAGRO for its Spanish acronym), a second-tier bank that is responsible for encouraging investments and sector development through commercial banks, in particular the Agricultural Bank of Colombia (Banco Agrario de Colombia)[24]. According to the historical information on agricultural credits in Colombia, between 2003 and 2014, 75% were granted through FINAGRO[25,26]. Regarding banking coverage, Echavarría et al.[26] mention that in 2016, around 75% of the rural municipalities in Colombia had at least one financial entity circumscribed. Likewise, ASOBANCARIA[27] states that in 2019, the banking sector has increased its coverage to nearly 100% of the country's municipalities, i.e., through the diversification of channels through bank correspondents who, on behalf of a bank, perform various operations, usually of a simple or low-cost nature for the bank[28].

The relationship between credit and agricultural production in Colombia has been studied mainly for the coffee sector. Evidence shows that access to credit has potential effects on improving coffee farmer's welfare, i.e., the credits granted between 2006 and 2014 have helped to improve the quality-of-life index of the studied coffee farmers by three times[29]. Like the coffee sector, the cattle sector plays a crucial role in the Colombian economy,

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since it generates around 1.1 million direct jobs, representing 6% of the national and 19% of the agricultural employment[30,31]. Between 2004 and 2014, 24.6% of the total agricultural credits were granted to the cattle sector, a number that was only surpassed by the coffee sector (30%)[32].

Despite its economic and social importance[33], (extensive) cattle ranching in Colombia is causing numerous negative environmental impacts, such as deforestation[34], which puts it at the center of debates around ecological conservation. The cattle sector is held responsible for approximately 60% of the country's deforestation, which is resulting from production inefficiencies, land use conflicts, and land speculation/grabbing, that drive cattle producers towards the expansion of the agricultural frontier[35–37]. Since cattle ranching in Colombia involves a strong land-use component, the increase of cattle herds is in most cases linked to the expansion of pastures, despite the availability of technologies, such as improved forages, that allow using existing pastures more intensively and sustainably[38,39]. In 2019, one hectare pastureland on average fed less than one animal and the 27.9 million cattle heads were maintained on 34.4 million hectares of grazing land[40–42]. If the current extensive land-use model for cattle production is being maintained, the inefficiencies of the sector will also remain and further increase the already strong effects on the environment (e.g., greenhouse gas emissions, water use, loss of biodiversity, and deforestation)[36]. Not to mention that these adverse effects on climate change will also affect cattle production in the country, i.e., animal welfare, feed and water availability, heat stress, and mortality, and thus cause economic losses[43–45].

The concern for deforestation and climate action also responds to several SDG, such as Good Health and Well-Being (UN-SDG 3), Affordable and Clean Energy (UN-SDG 7), Sustainable Cities and Communities (UN-SDG 11), Responsible Consumption and Production (UN-SDG 12), Climate Action (UN-SDG 13), and Life on Land (UN-SDG 15), and has thus an important role in the political agendas of most countries at both the national and local scale, which increasingly focus on finding a balance between increasing agricultural productivity and production and the environment[15].

In this order of ideas, it is relevant that the research focused on identifying and quantifying the effects of different strategies on agricultural productivity, has as a second objective of analysis to understand the effects on the life on land, especially forests, the loss of biodiversity, the climate, and the possible adverse effects that these bring for human well-being. This type of research is a fundamental input to propose local climate action strategies, responding to the so-called need for a "localization of the SDG"[46], which refers to the process in which local strategies are defined, implemented, and followed to achieve the SDG[47,48], considering that the current climate risks and vulnerability to deforestation can be directly associated with economies related to the extraction and overuse of natural resources[49].

Increasing both the (sustainable) intensification of the cattle sector and productivity levels through credit may cause unintentional effects on the environment, such as increased deforestation levels, even if credits are not destined for pasture extension[50,51]. Research shows that decreasing deforestation can be found when intensification occurs in already consolidated agricultural regions and increasing deforestation when it occurs on marginal lands[52,53] or when land tenure is unclear[54]. It should be noted that deforestation is also a spatially self-correlated phenomenon[55], highlighting the importance of a discussion on spatial effects and existing local mitigation policies. In Colombia, a series of national and local policies have been developed for supporting the adaptation to and mitigation of climate change in the cattle sector. These include e.g., The National Strategy for Reduction of Emissions by Deforestation and Forest Degradation and The Colombian Strategy for Low Carbon Development, among others[45].

In this case, integrating cattle production and local climate action turns out to be an urgent task for communities and other actors involved in beef and milk production and climate change policy at different scales. Articulation at the regional and national level between the key actors of the agricultural and environmental sectors is fundamental. Local climate action strategies will be successful if the conservation strategies in the territories do not imply economic loss or implications for the livelihoods of the producers and rural population.

This study analyzes the effects of agricultural/cattle credit on both cattle production and deforestation in Colombia. In addition, by using spatial panel data models, the study analyzes if spatial effects of credit distribution come along with spillover effects on the cattle herd and deforestation. This study contributes to two major political debates currently on-going in Colombia, namely (i) how to sustainably intensify cattle production systems considering a constantly increasing demand for animal-sourced foods and the negative impacts of cattle production on the environment, and (ii) how to reduce deforestation rates and contribute to ecological conservation of fragile and threatened ecosystems, such as the Amazon.

Results

Descriptive analysis and first considerations

The descriptive analysis suggests that, although important efforts have been made to make the financial sector more accessible, both the offices of the Agricultural Bank of Colombia (Fig. 1)[56] and the granted credits for the overall agricultural sector (Fig. 2) are still concentrated in the Central-Andean region where the largest part of the country's population lives in urban centers. This unequal distribution could be directly affecting the access to credit by rural producers who are further away, since traveling to an office involves time (the road infrastructure is underdeveloped in most rural areas) and high costs, which producers not necessarily are able to cover. Regarding the credits granted exclusively to the cattle sector, data suggests that credit distribution coincides with the main cattle production areas and thus a relationship between these variables can be intuited (Fig. 3). Like for the overall agricultural sector, credits for the cattle sector are concentrated in the central-Andean region of the country.

The historical analysis of granted credits for both the agricultural sector and the cattle sector between 2011 and 2021 (Supplementary Fig. 1) shows a general growth of over time, i.e., since 2016, with a peak in 2020, which might be attributed to granted emergency credits during the peak of the COVID-19 crisis. The credits under FINAGRO conditions are funded through three different sources, namely (i) the rediscount resources or discounted portfolio, which corresponds to the credits placed by financial intermediaries with FINAGRO resources, (ii) the substitute portfolio, which corresponds to resources of private financial intermediaries, and (iii) the agricultural portfolio, which corresponds to resources of the financial intermediaries not validated as a substitute portfolio[57]. These sources differentiate and determine where the funds come from and whom they will benefit. During the period of analysis, it can be observed that for the cattle sector, the amount associated with substitute portfolio credits exceeds the others since 2017 and that the agricultural portfolio is almost insignificant considering the other sources (Supplementary Fig. 1). Substitute portfolio credits are associated with private financial intermediaries, which increases the risk of lending to people with little collateral and might cause that FINAGRO credits are concentrated among large producers and those living in urban areas.

The analyzed data on deforestation shows that between the 2014–2015 and 2017–2018 periods, the loss of natural forest in the departments of Vichada, Guaviare, and Caquetá, which are part of the Amazon and Orinoco regions and subject to the extension of the local cattle sector, increased considerably while it decreased in the Nariño and Cauca departments (Fig. 4). This suggests a relation between deforestation and cattle production.

Supplementary Tables 1 and 2 provide information on the descriptive statistics of the analyzed dependent variables cattle production and annual deforestation rates, and Supplementary Table 3 shows a preliminary analysis of correlations between the independent and the dependent variables, which shows that there exist independent variable effects that make modeling necessary.

Econometric results: cattle production

Table 1 shows the results for the dependent variable cattle production, based on OLS, panel data with FE, and the spatial panel data models SAR, SEM,

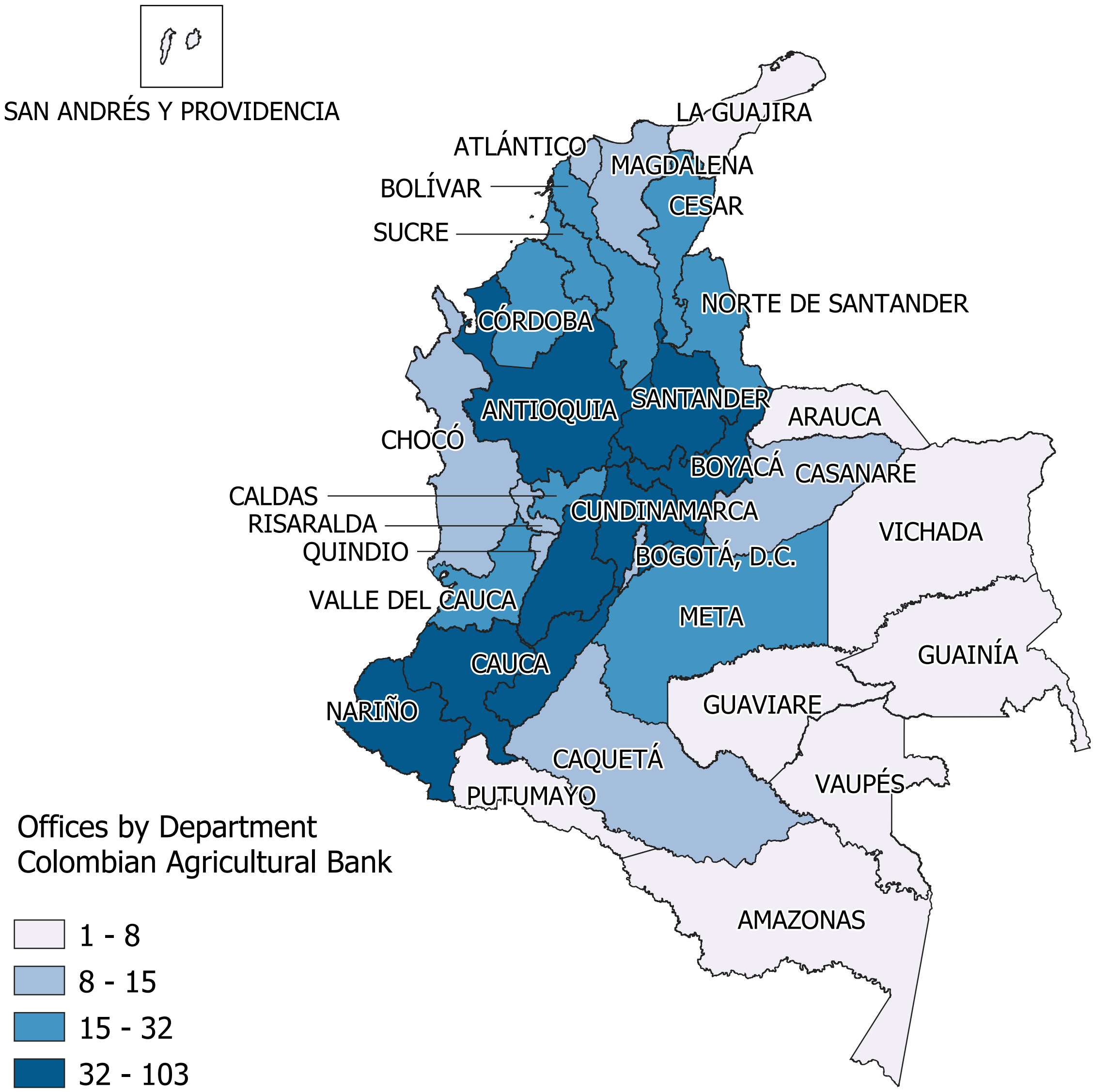

Fig. 1 | Distribution of branches of the Agricultural Bank of Colombia by department. Although important efforts have been made to make the financial sector more accessible, the branches of the Agricultural Bank of Colombia are still concentrated in the Central-Andean region where the largest part of the country's population lives in urban centers. Source: Author's elaboration based on ref. 56.

and SARAR. Initially, the regression was done using the simple OLS model but since this does not help in identifying the effect of different potential pre-existing conditions within each unit (department), the specification of panel data with FE was included. The FE analysis shows that access to credit and land use are significant for cattle production. Subsequently, it was assumed that, in addition to the existing relationships within each department, there are also spatial relationships between departments necessary to model. To select the best model, we used a simple and robust LM test for the dependence of spatial delay and spatial error. The robust error is significant, suggesting that a model with dependence on spatial delay and spatial error best fits the data, such as the SARAR model. It is worth highlighting that in spatial models, it is more interesting to consider spatial spillover (changes that occur in one region or department that have impacts on others)[58]. Therefore, the focus is on the direction of the coefficients, but less emphasis is placed on the coefficients until reaching direct and indirect effects.

The data shows that the only non-significant variable in any of the considered specifications is coca (hectares), meaning that there is no latent relationship between the number of hectares of coca that a department grows and its cattle production. Regarding credits granted by FINAGRO, it can be observed that the number of credits has a positive relationship with cattle production while the total amount disbursed has a negative relationship. Contrary to this, credits for the cattle sector present a positive relationship if the credit amount is considered and a negative relationship if the total number of credits is evaluated. A reason could be that the total number of credits is not considering if the individual credit amounts are so low that they are not used to expand the cattle herd but to improve other parts of the productive system. On the other hand, if the disbursed amount is considered we can see that, especially for high and very high amounts, at least a large part of the credit is allocated to expanding the cattle herd.

The proportion of rurality in a department is strongly significant regarding all the specifications, which proves the importance of this population for the agriculture and livestock sector. Considering land use, it can be observed that if the amount of land used for agriculture increases, cattle production decreases, while if the amount of land used for cattle increases, cattle production significantly increases, too. This coincides with what was expected from theory since agricultural and cattle production cannot be conducted in the same space, meaning that they are mutually exclusive.

One of the main advantages of spatial models is to be able to see spillover effects between geographic units. Table 2 shows the direct and

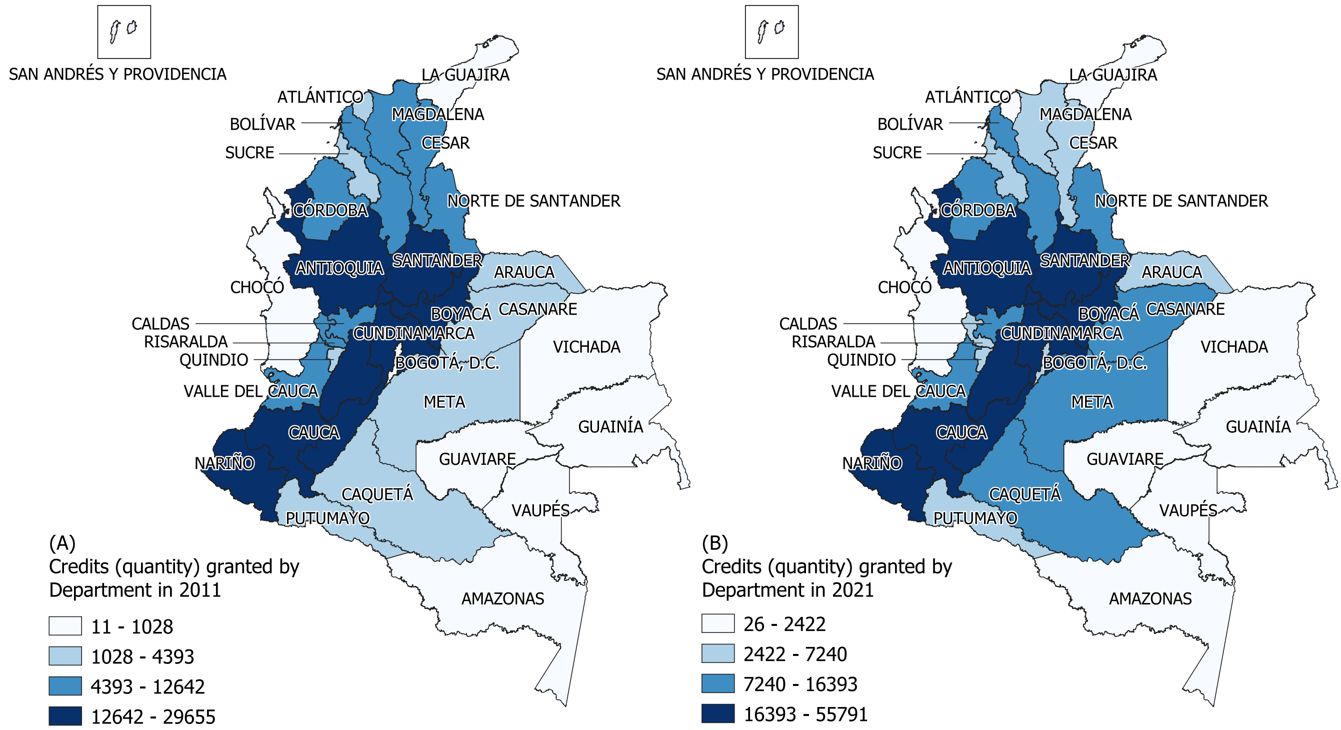

Fig. 2 | Evolution of the credits granted by the Agricultural Bank of Colombia in each department between 2011 and 2021. Although important efforts have been made to make the financial sector more accessible between 2011 and 2021, the granted credits by the Agricultural Bank of Colombia for the agricultural sector are still concentrated in the Central-Andean region where the largest part of the country's population lives in urban centers. Source: Author's elaboration based on ref. 56.

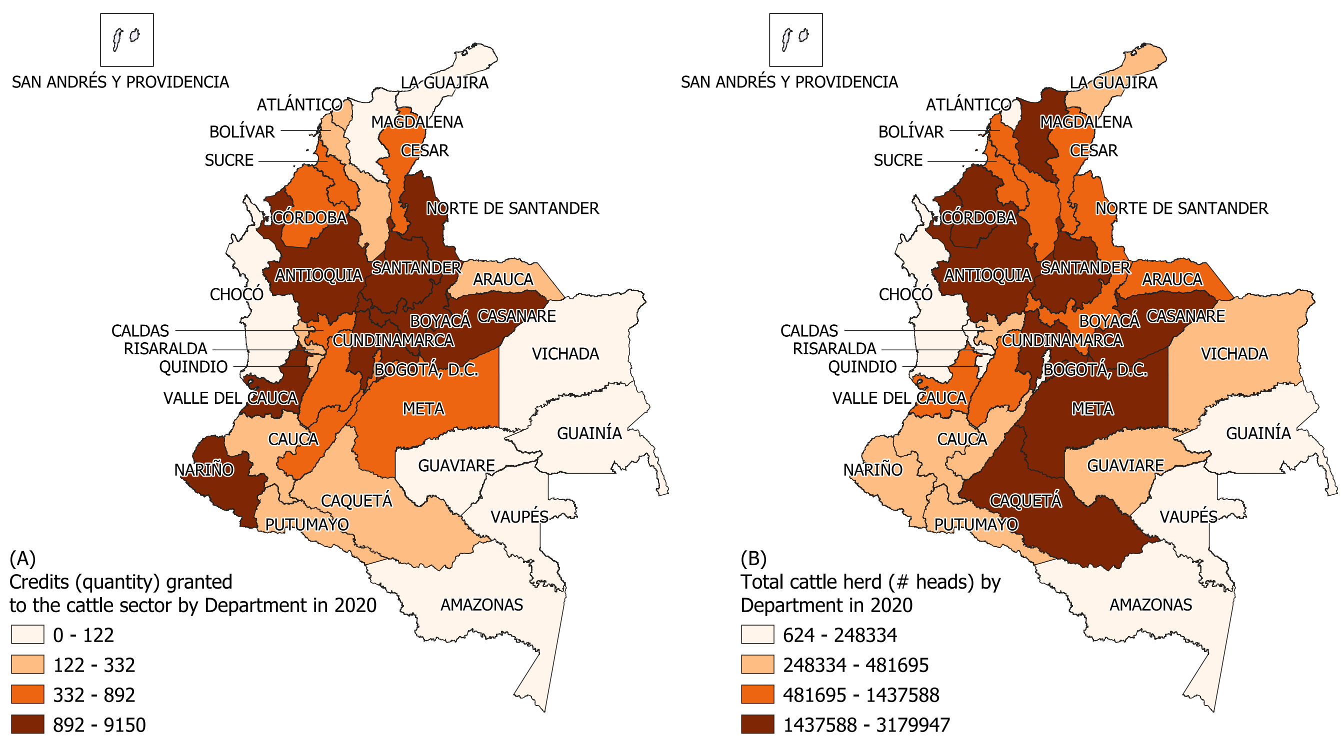

Fig. 3 | Credits granted to the cattle sector and cattle herd by department in 2020. The distribution of credits disbursed to the cattle sector coincides with the main cattle production regions and thus a relationship between these variables can be intuited. Source: Author's elaboration.

indirect impacts spatial spillover effects cause. The direct impact represents the change in the dependent variable for a particular department if the explanatory variable for that department changes. The indirect impact is the change observed in the other departments. It can be observed that there are no significant indirect spillover effects since all impacts occur directly and totally. In terms of credit, the impact is positive with the total number of cattle credits as well as their credit value, while it is negative for the total agricultural credit value and the total number of cattle credits. This shows

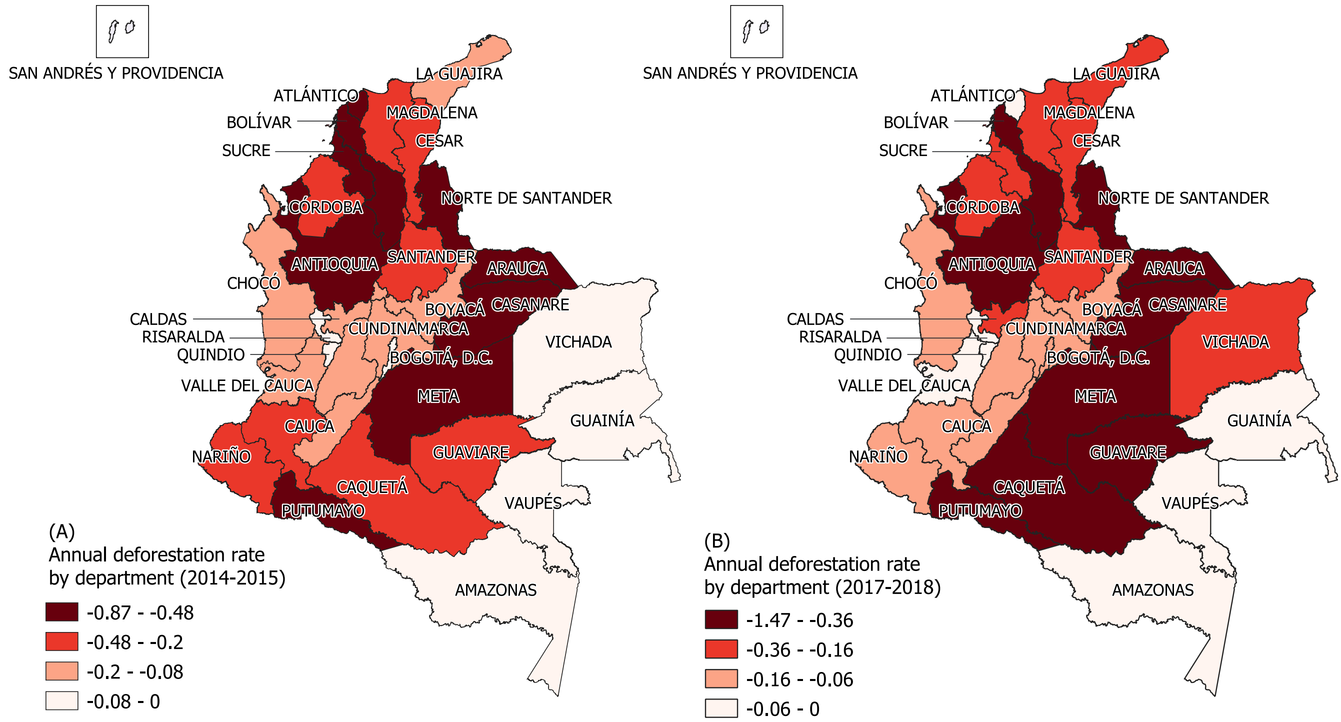

Fig. 4 | Development of the annual deforestation rates in Colombia for the periods 2014–2015 and 2017–2018. Between the periods 2014–2015 and 2017–2018, the loss of natural forest in the Amazon and Orinoco regions, which are subject to the extension of the local cattle sector, increased considerably. Source: Author's elaboration.

that, although access to credit within a department is significant because it influences cattle production in the same department, this relationship is ambiguous since the number of credits can indeed boost cattle production, but it is rather the credit values that make a change.

Econometric results: annual deforestation rate

Table 3 shows the results using the annual deforestation rate as dependent variable. This was done considering the OLS model and the panel data model with random effects (RE) since no evidence for spatial dependence was found. The results of the OLS model show that all but two variables (both related to credit) are having significant effects on the annual deforestation rate. As this specification might be biased because no relationships can be identified within the units, a Hausman test (see Supplementary Table 5) was conducted. It can be observed that the panel data model with RE suits better than OLS and that there are some differences between the OLS and RE specifications, especially in the significance of some variables. This results from the ignored relationships within the units if OLS is used and leads thus to overestimating the effects of the independent variables.

The results of the RE model show that the significance of the variables coincides with the estimations for cattle production as dependent variable. It can be observed that the variables cattle herd size, cattle land use, % rurality, and coca (hectares) influence the annual deforestation rates in the departments. The variables cattle herd size and cattle land use, have an inverse and significant effect on the annual deforestation rates, meaning that when cattle production increases, deforestation rates also increase.

The relationship between the variable coca (hectares) in a department and its deforestation rate is also inverse, showing that despite cattle farming is an important cause of deforestation, there are other activities, among them the cultivation of illicit crops, that also contribute to deforestation. It can be observed that the coefficient associated with cattle herd size is even lower than the one associated with coca (hectares). Finally, the value associated with the constant is high and significant. Although it is not correct to associate an interpretation per se with the constant, this is modeled in part to consider the possible omission of predictors from a regression analysis. For this reason, there might be omitted variables in this analysis.

Discussion

The results of this Colombian case study, although not having external validity, are in line with other research on the relation between agricultural credit and production. Based on the mapping of the relevant variables, this study shows that the distribution of both the number of branches of the Agricultural Bank of Colombia and the total number of credits granted by FINAGRO correspond to a structure known as the national center-periphery structure. This structure assumes that in a country, territories located closer to the center or capital (in the Colombian case the Central-Andean region) are more advanced than those located in the periphery[26,59]. A center-periphery structure causes the developed center, which is presumed to be industrialized, educated, and with control over resources, to increase its productivity rates more and faster compared to the underdeveloped periphery, which is presumed to be focused on agriculture and mining, is illiterate, and has limited resources[60]. Regarding access to credit, this structure results in increased costs and limited access because the lack of entities in place and the requirements imposed by the formal banking sector generate incentives for large producers and those living in or close to cities, even in the studied case where credits are entirely destined to the agriculture and livestock sector. In this regard, data from official sources[61] show that agricultural credits manage to cover only about 38% of the country's rural producers. Regarding the credits disbursed under FINAGRO schemes, both for the entire agricultural sector and for the cattle sector, the year 2020 meant a considerable increase in the number of credits placed, which is related to incentives and financial reliefs proposed by the National Government to face the economic crisis caused by the COVID-19 pandemic and its mitigation measures[62,63]. Consequently, the agricultural sector in 2020 received the highest credit placement since statistics are available, with an increase in 2020 of 26% in credit value and 24% in the number of credits compared to 2019[64].

Regarding the effects of credit on cattle production, the results obtained from the econometric models coincide, to a large extent, with what is documented in literature. When it comes to land use, this study shows that if more land is used for agriculture, cattle production decreases (inverse relationship), while if more land is used for cattle, cattle herd sizes and thus cattle production also significantly increase (direct relationship). This is in

Table 1 | Model estimations with cattle production (herd size) as dependent variable

Dependent variable: cattle production (herd size)					
Variables	OLS	FE	SAR	SEM	SARAR
Number of agricultural credits		11.1174**	7.7976*		7.6494*
		(4.3180)	(4.0731)		(4.20E+00)
Total credit value agricultural credits	−0.3429***		−3.0070e−01**	−0.29719**	−0.30548**
	(0.1192)		(0.10846)	(0.10888)	(1.10E−01)
Number of cattle credits	−111.6304***		−1.4431e+02***	−1857.89***	−151.76***
	(33.4814)		(29.532)	(30.262)	(3.03E+01)
Total credit value cattle credits	3.0620***	1.0002*	2.5421e+0**	2.6107***	2.6055**
	(0.8548)	(0.5238)	(0.78966)	(0.77541)	(7.92E−01)
Coca (hectares)					
Agricultural land use			−7.3207e−01*	−1.0126*	−0.85427*
			(0.42241)	(0.44366)	(0.43611)
Cattle land use	0.3001***	−0.0481*	2.8863e−01***	0.29898***	0.29884***
	(0.0354)	(0.0265)	(0.03125)	(0.033735)	(0.032774)
AgriculturalBank of Colombia offices (#)	12,005.1045***		12612***	13022***	13017***
	(2,167.6712)		(1978.9)	(2023.4)	(2021.6)
% Rurality	−527513.5352**	1730356.7720**	−6.7552e+05***	−863290***	−764350***
	(240,876.1994)	(819,586.8440)	(190630)	(225750)	(207470)
Lambda			0.320157***		0.210559*
			(0.052533)		(0.093001)
rho				0.436734***	
				(0.062277)	
R-squared	0.5274				
LM Test (lag)	2.3287				
Robust LM Test (lag)	5.9633**				
LM Test (error)	0.90077				
Robust LM Test (error)	4.5353**				

Standard errors (robust) in parentheses.
The variables that do not appear in the table do not show statistical significance.
Source: Author's elaboration.
***$p < 0.01$; **$p < 0.05$; *$p < 0.1$.

line with the findings of other studies for the entire agricultural sector, which describe that the planted area and its yield are positively related to increases in agricultural productivity[65]. In fact, the relationship of agricultural land use and production found there has a coefficient of 0.13 while the relationship of cattle land use and cattle production found in this study has a coefficient of 0.29, indicating that land concentration is more important in the cattle sector than it is for agriculture in general terms. The positive relationship between land use and agricultural and cattle production motivates the expansion of the agricultural frontier, especially on marginal lands[52] and when land tenure is unclear[54], even if sustainable production technologies are being promoted (Jevons paradox[66]). It is thus essential to find local climate actions that mitigate the effects of agriculture and cattle on deforestation. In the Amazon, moderate success of the Soy Moratorium and Cattle Agreements were documented[67], for example, but further strategies are required to prevent cattle producers from expanding their land through deforestation. This includes, for example, a combination of the credit incentives and monitoring and control mechanisms (e.g., deforestation monitoring, traceability, taxes on the use of conventional technologies)[33,68–70].

Access to credit has differential effects if the total number or the total values are considered and if they are destined to the agricultural sector in general or to the cattle sector. This differential effect can make the impact of access to credit significant or not and direct or inverse. In this study, all variables related to access to credit are significant, meaning that the total number of agricultural credits, the total value of cattle credits, and the number of offices of the Agricultural Bank of Colombia have a direct effect on cattle production, while the total agricultural credit value and the number of credits for the cattle sector have an inverse effect. This statistical significance between access to credit and agriculture and cattle production coincides with what was found for the coffee sector[29], where, depending on the specification considered (FE or instrumental variables), access to credit increases coffee production by approximately 30%. It is also in line with the findings made for the cattle sector in Brazil[51], which document that access to credit incentivizes the purchase of more cattle (on average 27 animals among producers with access to credit versus 5.2 animals without). It furthermore coincides with a study from Ethiopia[71], which describes that credit is positively related to the level of consumption (with a coefficient of 0.018), showing that access to credit creates the capacity to increase agricultural and livestock production, and with findings from Rwanda[12], which suggest that families with access to microcredits have more cattle, more productive capacity, more income, and more economic security than those without access. Our results differ, however, from findings made for the overall agricultural sector in Colombia[65], which document that when agricultural production is spatially modeled, the total credit values are not significant since capital investment fails to coincide in a contemporary way in production. This could show intrinsic differences between agricultural and cattle production, since in the former it takes time to observes the results while in the latter effects might be more direct.

Additionally, this study shows that the distribution of cattle production and credits respond to spatial correlations, which coincides with studies

Table 2 | Estimation of direct and indirect impacts of spatial spillover effects

	Direct	Indirect	Total
Number of agricultural credits	15.63	−5.94	9.69*
Total credit value agricultural credits	−0.62*	0.24	−0.39***
Number of cattle credits	−310.14**	117.90	−192.24***
Total credit value cattle credits	5.32*	−2.02	3.30***
Coca (hectares)	1.35	−0.51	0.84
Agricultural land use	−1.75	0.66	−1.08*
Cattle land use	0.61**	−0.23	0.38***
AgriculturalBank of Colombia offices (#)	26601.84**	−10112.91	16488.93***
% Rurality	−1562035.00*	593820.60	−968214.30***

Source: Author's elaboration.
***$p < 0.01$; **$p < 0.05$; *$p < 0.1$.

Table 3 | Model estimations with annual deforestation rate as dependent variable

Variables	OLS	RE
Cattle herd size (heads)	−1.6E−07***	−9.3E−08*
	4.57E−08	4.97E−08
Agricultural land use	6.5E−07*	
	3.7E−07	
Cattle land use	−6.64E−08**	−5.21E−08*
	2.84E−08	(3.12E−08)
Number of agricultural credits		
Total credit value agricultural credits	3.1E−07***	
	1.1E−07	
Number of cattle credits	6.8E−05*	
	2.7E−05	
Total credit value cattle credits		
% Rurality	0.8722***	0.5812*
	(0.1911)	(0.3047)
Coca (hectares)	−1.3E−05***	−8.5E−06**
	3.2E−06	4.0E−06
Constant	−0.5857***	−0.4905***
	(0.0723)	(0.1159)

Standard errors (robust) in parentheses.
The variables that do not appear in the table do not show statistical significance.
Source: Author's elaboration
***$p < 0.01$; **$p < 0.05$; *$p < 0.1$.

conducted for the coffee sector in Colombia[29], the cattle sector in the Brazilian Amazon[51], and the agricultural sector in Colombia[65]. As described for the latter[65], positive and significant spatial dependency parameters (0.43 in the case of the present study) mean that if a positive shock is perceived in a department, not only will production in that department grow faster, but this impulse will also make production grow in nearby departments because of a contagion effect. It is also observed that there are effects with a lag, meaning that effects can be observed today if in the past years there has been an increase in the access to credit.

Regarding deforestation, the results of the econometric models also largely coincide with literature. Cattle production has a negative and significant effect on the annual departmental deforestation rates, meaning that if the cattle herd increases and more land is used for cattle production, deforestation rates also increase. This result coincides with findings for the cattle sector in the Brazilian Amazon[51] and on deforestation in Colombia[72] and highlights the importance of the cattle sector for the mitigation of negative environmental effects. In the case of Colombia, it is important to highlight that there are several studies on habitat destruction and deforestation following the government's peace agreement with the Revolutionary Armed Forces of Colombia (FARC) e.g., refs. 73–79. The presence of armed actors in protected areas such as forests, although unwanted, somewhat slowed down the exploration and deforestation of these areas by other actors[74]. Some cattle producers see this as an opportunity to expand the area dedicated to cattle farming through deforestation. In fact, for the post-conflict period since 2016 there is evidence that cattle and not illicit coca farming is the main driver of forest loss outside the legal agricultural frontier[73]. Local climate action should thus propose strategies to stop the expansion of illicit cattle expansion and farming.

A solution to this can be found in sustainable intensification[38], where the employment of sustainable production systems, based on e.g., improved forages or silvo-pastoral systems, is intended to, among others, reduce the pressure on land and the expansion of the agricultural frontier, while increasing productivity. Nevertheless, increasing the productivity of cattle production systems, even in a sustainable way, can also lead to contrary effects and further contribute to deforestation (Borlaug effect)[33]. Studies from Brazil[70,69], for example, show a large mitigation potential of an intensified cattle sector if intensification is coupled to policy instruments, such as no-deforestation, taxes on conventional production systems, and subsidies for sustainable intensification. Other studies[52,53] highlight the influence a region or land tenure conditions can have on land-use changes resulting from agricultural intensification, i.e., the risk of deforestation is lower when intensification takes place in consolidated agricultural regions than when it happens on marginal lands. Deforestation also increases when land tenure is unclear[54]. This coincides with the findings from this study, since most of the deforestation in Colombia takes place on rather marginal lands where land tenure is often unclear (e.g., in the Amazon and Orinoquía regions). Additionally, a meta-analysis of over 60 studies[68] found that only in few cases, agricultural intensification comes along with positive effects on both well-being and ecological conservation. The findings from literature and the present study suggest that for the sustainable intensification of the cattle sector to be successful in Colombia, several policy and market mechanisms are required. This includes monitoring, law enforcement (i.e., in marginal, conflict-affected regions such as the Amazon), subsidies, taxes, and clarity on land tenure, among others[33]. In this regard, Colombia is already making strong advances, for example through the establishment of the National Zero Deforestation Agreements[33], the first public policy on sustainable cattle[80], new credit lines for the establishment of silvo-pastoral systems[63,81], and product differentiation[82–84], among others. It is yet too early, however, to make conclusions about the effectiveness of these instruments. Thinking specifically on credits and financial instruments that promote climate action in cattle production, articulated work between different stakeholders in the value chain of this sector is necessary. At the national level, the design and promotion of a clear credit policy for sustainable cattle is required. The Ministry of Agriculture and FINAGRO should design new financial instruments, that are accessible to and include adequate conditions for producers and consider benefits for the achievement of environmental goals. Afterwards, the commercial alliance between the Ministry of Agriculture, FINAGRO, and financial institutions throughout the country needs to be expanded to distribute the available resources adequately (and not only through the Agricultural Bank of Colombia). At the local level there are two fundamental allies: (i) the municipal governments, which through their rural extension programs can provide advice and technical support to producers who receive credits and report to the bank their compliance with the environmental goals established to access the credit and its benefits; and (ii) producer associations that can promote these credits among their members and help them access them.

Studies on deforestation from the Brazilian Amazon[55,85] found that access to credit has a direct and significant impact on deforestation. The present study, however, suggests that neither the total number of credits for the agricultural sector nor those for the cattle sector have significant effects on the annual deforestation rates. This coincides with another study on deforestation in the Brazilian Amazon and the role of the cattle sector in this regard[51], where the initially postulated hypothesis that access to credit and deforestation rates are correlated was rejected. This result might be, at least in part, related to one of the weaknesses mentioned in the methodology section: the consulted data on deforestation rates used in this study originates from IDEAM[86], whereas other studies[55] could rely on data derived from satellite images. The missing correlation between credit and deforestation might also be related to omitted variables in the model, since it is not possible to include variables related to the armed conflict or other political and social circumstances that might have effects of deforestation.

Finally, literature suggests that deforestation could be considered a spatially correlated phenomenon[51,55], meaning that deforestation observed in a particular region is not only being affected by the decisions made in that region but also by decisions made in neighboring regions. A study from Brazil[55], for example, describes that if cattle producers plant pastures that require periodic burning, this affects the decisions of their neighbors, since the logical answer is to follow the same example given that the pastures are adapted to fire. In the present study, however, no evidence of spatial correlations with the selected variables at the departmental level were found. It is possible that if our analysis was performed at the municipal level or even at the individual level (like[55]), the evidence would correspond to the literature, but due to a lack of available data this was not possible.

In summary, this study evaluates the effect of access to credit on cattle production and deforestation rates at the departmental level in Colombia, also considering potential effects of spatial patterns. It is a valuable contribution to the existing empirical evidence that allows policy and decision makers to understand the failures and limitations related to the access to credit for incentivizing production and propose more effective and efficient policies to support both cattle production and ecological conservation, i.e., of forests and protected areas.

Considering that access to credit in general and its effect on agricultural production have been widely studied throughout the world, the literature review in this study revealed that there are ambiguous effects, meaning that the effect of access to credit on production depends on (i) whether the total number of disbursed credits or their total amount are considered and (ii) the immediacy of the agricultural activity that is being funded through credit, since it is possible that these are not temporally correlated. Regarding the cattle sector, it was found that access to credit has significant effects in all cases. There is no common agreement in literature that reveals whether the relationship is also spatially correlated, and this study thus aimed at closing this gap. Evidence was found documenting the existence of a spatial relationship between credits for the cattle sector and cattle production.

The study responds to a specific period for which data was available and the results thus may vary if more data is included or if data is considered at a more disaggregated (municipal or individual) level. Nevertheless, evidence is provided showing that access to credit has influence on cattle production. Both an increase in the number of credits placed in a department as well as in the credit values destined to the cattle sector also increase cattle production in the same department. The study further provides evidence on the negative effect of cattle production on deforestation rates but also highlights that cattle production is not the only cause of it. Including further differential factors associated with social, legal, and economic phenomena, such as the COVID-19 pandemic and the peace process, among others, is recommended for future analyses, since this would help to fully understand the drivers behind deforestation. In terms of data on deforestation rates and given the difficulties this study experienced with this indicator, it is recommended to change the way deforestation is currently measured in Colombia. Satellite imaging could be a solution and helped to provide more solid results in studies conducted in Brazil, for example. This data is crucial for providing more profound analyses on the causes of deforestation, considering the specific conditions and dynamics within a department or municipality, that lead to more adapted, effective, and efficient policy instruments for ecological conservation.

The results support policy making processes that focus on incorporating credit into production growth models. The need for strategies aimed at expanding the coverage of credits, i.e., in (remote) rural areas, is recommended and could be achieved, e.g., through increasing the number of bank branches in the peripherical departments, so that the credits can effectively reach those who need them most and are no more concentrated mostly among large producers from the interior of the country (center-periphery model). To expand the coverage of FINAGRO credits in remote regions where it is not economically viable to open branches, the exploration of alternative strategies, such as alliances with local microcredit institutions, financial cooperatives, and municipal administrations, is recommended. An interesting option in this regard are non-traditional formal credits through microfinance institutions, since they can more easily react to problems related to risk aversion, information asymmetry, and moral hazard. However, for these institutions to become a recognized alternative, they need to start collecting records on the credit they provide and on credit-worthiness of their customers. The rural credit expansion requires the promotion of banking and banking literacy among the rural population through strategies that facilitate procedures and reduce the transaction costs associated with having financial products. The results highlight the importance of future cohesive policies at the departmental level for access to credit and of generating channels between departments to improve efficiency. Credit policies must be guided by uniform and transversal criteria, at least in the regions where cattle production plays a major role.

Regarding local climate action strategies based on credit instruments, the expansion of cattle credit should be linked to pre-conditions that help assuring a sustainable growth of the sector and ecological conservation. It is thus recommended that prior to granting credit, a verification of no deforestation in the registered properties is assured. It is also recommended that the reduction of negative environmental impacts of cattle production is incentivized through the access to specific credit lines for sustainable intensification, e.g., for the establishment of silvo-pastoral systems, which comprise reduced interest rates that are dependent on the compliance with environmental criteria. This process requires technical support to producers through rural extension or technical assistance programs that help with knowledge and technology transfer related to sustainable production alternatives. Such support can directly come from the banks and be aligned to the granting of credits. Likewise, public rural extension programs need to be strengthened and focus more on sustainability. This approach, however, needs to be aligned with other policy and market mechanisms and instruments, such as monitoring schemes, law enforcement, subsidies, and taxes, that help preventing negative environmental impacts related to sustainable intensification of the sector (Borlaug effect).

Methods

Literature review

Studies on the impacts of agricultural credit in Latin America were mainly conducted in Peru[1], Colombia[29,65], Brazil[23,51], and Chile[87]. At the global level, studies can be found for Africa[12,71], Southeast Asia[19], and China[14,88]. Most of these studies have a more general focus and consider agricultural production in an aggregate way[1,14,19,65,87]. Within the studies conducted in Latin America, however, coffee[29] and cattle[23,51] stand out as specific sectors of analysis given their importance at the social and economic levels, i.e., for employment, income generation, and Gross Domestic Products. In general, these studies reveal a positive and direct relationship between formal credit and agricultural production. Producers who have access to formal credit are, for example, better situated regarding quality of life, productive capacity, social status, and some covariates of poverty[12,29,65,71]. Other studies point out that the main limitation for rural development is access to formal credit and suggest alternatives for improving financial inclusion within rural populations[1,14,19].

The objectives of the studies vary, however, and range from improvements in the living conditions of the producers[12,29,88] to increases in agricultural production and consumption[65,71] and investment[14], effects on deforestation[51], and the adoption of technologies[23,51]. Consequently, the applied methods also vary. Some scholars[14,19,23] approximate the effects of credit through sampling, surveys and/or semi-structured interviews. Impact evaluation is also being widely used due to its statistical rigor and the possibility of comparing treated and control groups[12]. Lastly, other scholars approach the topic with more rigorous methods, such as the ordinary least squares model, panel data models, and instrumental variables[29,71].

Despite potential spatial relationships in agricultural production in a territory, there do not exist many studies that relate credit and agricultural production at a spatial level. This approach is, however, suggested by various scholars[65,87,88] as the most appropriate since if the unit of analysis responds to territories, not considering that this distribution may not be random would mean to remain with a static look at the problem. The present study thus contributes to the scarce literature by providing robust evidence using sophisticated spatial models.

Regarding the relationship between cattle, productivity, and deforestation, three specific streams of research can be identified, namely (i) academic research specifically related to climate action e.g., refs. 67,73–79, (ii) documents from multilateral organizations that warn of the effects of both extensive cattle ranching and agricultural credit on deforestation e.g., refs. 35,89,90, and (iii) academic research focused on the importance of local climate action. Regarding the second, it is emphasized that poor land management in extensive cattle ranching activities can have strong effects on deforestation and how, through credit, these practices can be discouraged. Regarding the third, the discussions focus on actions with a specific territorial focus, carried out by natural persons who, from their doing, seek to contribute to a reduction of the adverse effects of cattle farming on climate change. In this regard, the document developed by Tapasco et al.[45] stands out, where a series of recently developed policies are being discussed that seek to facilitate the large-scale adoption of mitigation and adaptation practices in the Colombian cattle sector. These include, for example, the Green Growth Policy formulated by CONPES in 2018, which specifies actions to increase productivity in a sustainable manner until 2030. The authors also state that Colombia has gained territory in terms of local mitigation actions and policies that involve cattle, since (i) the political space already exists with relevant institutions showing an interest in issues related to climate change, (ii) there is an institutional and associative space with broad integration between actors in the sector. However, they also note that there are still some weaknesses that inhibit the scaling of these policies, such as the availability of required public and private financing, and the little connection between learning spaces in the different regions of the country.

Data and variables

To examine the effects of credit on cattle production and deforestation, and to observe possible spatial relationships, a departmental data panel was constructed for the period 2011–2020. Colombia is a unitary and decentralized republic that is administratively and politically divided into 33 divisions, 32 departments (governed from their respective capital cities), and a capital district, Bogotá. Two dependent variables are proposed: (i) cattle herd size as indicator for cattle production and (ii) deforestation rate at a specific moment in time. First, the departmental effect of credit access on the cattle herd is modeled for the period 2011–2020 using control variables such as land use and sociodemographic characteristics. The dataset on the cattle herd was obtained from the Colombian Agricultural Institute (ICA, for its Spanish acronym)[91]. Second, the expected effect of an increased cattle herd on the annual departmental deforestation rates is modeled for the period 2012–2019. The difference with the period of analysis used for the first variable is a result of data availability. The data for the second variable were derived from the Institute of Hydrology, Meteorology and Environmental Studies (IDEAM, for its Spanish acronym)[86]. The annual deforestation rate is defined as the variation in the area covered by natural forest, in a certain spatial reference unit (department), between an initial year and a final year[36]. The independent variables considered are (i) access to credit[4–8], (ii) land use[35], and (iii) sociodemographic control variables[65].

(i) *Access to credit:* The total amounts and values of credits disbursed by FINAGRO by department are considered, both in terms of overall agricultural credits and credits specifically granted to the cattle sector. Likewise, data on granted credits are disaggregated according to different producer types. In Colombia[92], a small producer holds assets of up to 284 Current Legal Minimum Monthly Wages (CLMMW), a medium producer of up to 5000 CLMMW, and a large producer of more than 5000 CLMMW, respectively. In 2020, the CLMMW was 877,803 Colombian Pesos[93], which was equivalent to 237.60 USD[94]. The number of branches the Agricultural Bank of Colombia, as principal bank for granting FINAGRO credits, has in each department is considered as a proxy for the ease of access to the banking system. It is recognized that this assumes a methodological weakness, since a branch in one municipality can cover the demand of several neighboring municipalities.

(ii) *Land use:* The use of agricultural land and land destined specifically to cattle production was consulted from the National Agricultural Surveys (ENA, for its Spanish acronym)[95] for 2012–2015 and 2017–2019. The use of agricultural land is defined as the use of suitable land for a wide variety of crops due to its favorable conditions such as temperature, soil PH, fertility, and texture, among other factors[96]. Additionally, the number of hectares planted with coca at the departmental level are considered to observe the relationship of illicit crops with deforestation and cattle production. This database was obtained from the Colombian Drug Observatory[97], which provides historical information on coca cultivation (evolution in hectares) for the producing municipalities. It is assumed that there might be a relationship with land accumulation, land grabbing, and land speculation.

(iii) *Sociodemographic control variables:* The percentage of rurality is considered as a control variable. The population censuses carried out in 2005 and 2018[98,99] were consulted and a projection for completing the entire series until 2020 was calculated. The projection uses the available growth rate provided by the databases and assigns a year-by-year growth. After completing the population series for the whole period (2005–2020), the rural population and the total population are divided to obtain the percentage of rurality each year.

Methodological approach

Panel data models provide combined benefits between the use of cross-sectional data and time series, meaning that they manage to follow an individual (n) through time (t). Initially, panel data models assume that individuals are independent of each other, but that an individual's observations are mutually dependent[100]. Considering the availability of the variables for the entire period of analysis (2011–2020), the panel used in this document is an unbalanced panel. Panel data models pose challenges and benefits when estimating them. Although they can lead to distortions in the estimation of errors[101], they also manage to control individual heterogeneity, providing greater variability, less collinearity, and more efficiency[101,102].

There are two different specifications used in panel data models: fixed effects (FE) and random effects (RE). The FE specification is used when the decomposition of the error (the unobserved heterogeneity) and the idiosyncratic error are correlated, and it is therefore not possible to make an efficient estimation of the variance and covariance matrix[103]. FE assumes that the individual effect (n) is correlated with the explanatory variables[104]. To model the relationship between the access to credit and cattle production, considering that our individuals (n) are the 32 Colombian departments, the appropriate specification is FE, while for modeling the annual deforestation rate, the appropriate specification is RE (see Hausman test in Supplementary Tables 4 and 5).

This study also tests if there are spatial effects with credit and whether there are spillover effects between neighboring departments, considering that the units respond to data of a spatial nature[105–109]. For this and considering that space must be incorporated as one of the determinants of the interactions, spatial panel data models are used. In this sense, unlike the temporal dependence that is usually found when working with time series, where decisions made in the past can affect the present (unidirectional relationship), spatial dependence brings with it multidimensional relationships in which a region can be affected by another contiguous region or by several or all regions that make up the total territory[110]. Spatial interaction effects usually occur when individuals (n), located in space i make decisions based on the decisions of individuals located in space j[105,111]. This means that spatial dependence exists if the dependent variable in each geographic unit is partially a function of the same variable in a neighboring geographic unit[112]. The most common tool for measuring spatial interdependencies is known as the weight matrix or contiguity matrix (W), which is made up of 1 and 0 and shows the contiguity between two geographic units by having at least one limit in common. Although there is no single definition for the weights within W, the binary representation has been commonly accepted[113]. In this sense, the W matrix can be represented graphically thinking of a chessboard and responds with the movements that the queen can have (since all units i and j that share at least one limit in common will be neighbors).

There exists a protocol to determine if panel data models are adequate or not, the so called exploratory spatial data analysis (ESDA). This protocol focuses on testing atypical locations and spatial association schemes through locational similarity phenomena and is performed using two statistics: (i) Moran's I, and (ii) Geary's C. Having tested whether there is spatial dependence using these statistics (Supplementary Tables 1 and 2), it is possible to select the type of model to be applied, considering the specification that best models the relationship (Lagrange-Multiplier (LM) tests are considered). In this sense, the existing specifications are Spatial Autoregressive Models (SAR), Spatial Error Models (SEM), and Spatial Autoregressive Models with a spatial autoregressive error term (SARAR), among others[65]. For this research, a comparison is made between the Ordinary Least Squares (OLS) model, which does not consider spatial dependence, and the models mentioned above, since it is presumed that ignoring spatial dependence biases the results and generates inconsistent coefficients[114,115]. If there exists a spatial dependence that must be included in the model, according to the Moran statistic (Supplementary Figs. 3 and 4), the following spatial panel data models for the variable cattle production by department are being estimated:

$$\boldsymbol{SAR}: y_{it} = \rho W y_{it} + \beta_1 CreditAccess_{it} + \beta_2 LandUse_{it} + \beta_3 Sociodemographics_{it} + \varepsilon_{it} \quad (1)$$

$$\boldsymbol{SEM}: y_{it} = \beta_1 CreditAccess_{it} + \beta_2 LandUse_{it} + \beta_3 Sociodemographics_{it} + U_{it}$$
$$U_{it} = \lambda W U_{it} + \varepsilon_{it} \quad (2)$$

$$\boldsymbol{SARAR}: y_{it} = \rho W y_{it} + \beta_1 CreditAccess_{it} + \beta_2 LandUse_{it} + \beta_3 Sociodemographics_{it} + U_{it}$$
$$U_{it} = \lambda W U_{it} + \varepsilon_{it} \quad (3)$$

Where y_{it} refers to cattle production of department i in year t, W is the weight matrix or contiguity matrix, ρ and λ are the spatial dependence parameters of lag and error, respectively. $\beta_1 CreditAccess_{it}$ considers the effect of the variables associated with access to credit (number of total credits + amount of total credits + number of cattle credits + amount of cattle credits + number of offices of the Agricultural Bank of Colombia) of department i in year t. $\beta_2 LandUse_{it}$ considers the effect of the variables associated with land use (hectares planted with coca + agricultural land use + cattle land use) of department i in year t. $\beta_3 Sociodemographics_{it}$ considers the variable of rurality of department i in year t. ε_{it} is the error term. Supplementary Table 6 provides correlation tests for land use and cattle production, as well as land use and credit. A strong correlation between the variables associated with land use and cattle production, and a low correlation between the same variables and the variables associated with credit. Due to the above, it can be concluded that it is correct to consider the variables of land use as controls for the cattle herd in the Colombian case. Supplementary Table 7 provides correlation tests and joint significance tests for the four credit variables. Two combinations that may be potentially collinear are observed: a moderate positive correlation between number of cattle credits and number of agricultural credits, and a high positive correlation between total credit value cattle credits and total credit value agricultural credits. These correlations may occur due to the type of information that the variables contain (the number of credits or their amount). As a result, it would seem correct to select only those credit variables that do not present high correlations. However, the joint significance tests below show that the best model is the one that includes all four credit variables, since it manages to collect more information. The selected model in this study is thus the one that contains all four credit variables. Finally, Supplementary Table 8 provides a Cook distance test.

For the descriptive part of the analysis a graphical view of the georeferenced variables that will be used in the estimations later is provided through choropleth maps that correspond to the intensity of the considered variable[116]. For this, the free software QGIS 3.12 is used. For the econometric analyses of OLS and panel data with both FE and RE, StataMP 13 is used. For the spatial analysis and the SAR, SEM, and SARAR models, RStudio is used.

Study limitations

The database used in this document has a series of limitations that must be considered. First, it was not possible to disaggregate at the municipal level due to a lack of data. Although the analysis of a smaller unit (such as the municipal level) manages to provide clearer information, in this case it was necessary to work at the departmental level to include a database with more variables. Second, an unbalanced panel is used, which means that for a particular year or even several years, no data and thus no variables are available, leading to the generation of missing variables. This happened with the variables related to land use (for coca, agriculture, and cattle), where data is only available until 2019, meaning that for 2020, these variables are missing. Third, regarding the variables land use for agriculture and cattle, the data used correspond to the ENA, which are representative but self-reported surveys carried out annually, and thus poses the risk of certain inconsistencies with reality. As a result, conclusions made regarding their effect on production might be over- or undervalued. In addition to that, for some periods, data is not complete for all departments due to methodological issues that occurred with the survey at the time of data collection, since for 2017–2019, information was collected in 32 departments but for 2012–2015 in 22 departments only[95].

Regarding deforestation, there are several limitations in this study. First, the available information corresponds to the annual deforestation rate, which relates two periods in time and seeks to identify the variation in the area covered by natural forest. In this sense, it is possible that, methodologically, this variable is not correctly related to the independent variables since they correspond to a specific year and not to the change between one year and another. Second, due to difficulties IDEAM has in calculating annual deforestation rates, this data is only available for the period 2012-2018. Third, deforestation, although related to cattle farming, responds to social, legal, and economic phenomena (e.g., armed conflict, eradication of illicit crops, migratory waves, displacement of communities, and political interests)[72], and if these are not considered, the modeling might be biased. We mainly find two events that could alter the estimates provided in this study: (i) the agreement for the end of the armed conflict in Colombia and the construction of a stable and lasting peace (also known as the peace process)[72,74], and (ii) the COVID-19 pandemic and its mitigation measures, which both have strong impacts on the agriculture and livestock sector[62,63,117].

Reporting summary

Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

The datasets generated and/or analyzed for this study are available from the corresponding author on reasonable request.

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Author contributions

D.M., K.E., M.D., and S.B.: Conceptualization. D.M., K.E., A.B., F.F., J.J., and S.B.: Methodology. D.M., K.E., A.B., F.F., J.J.: Formal analysis. D.M., A.B., F.F., and S.B.: Writing the original draft and review and editing. D.M., K.E., M.D., and S.B.: Resources. S.B.: Supervision and funding acquisition. S.B.: Project administration. All authors contributed to the article and approved the submitted version. D.M. and S.B. are co-first authors of this article.

Competing interests

The authors declare no competing interests.

Additional information

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