The Differential Responses of Farmers on Private and Public Lands to Droughts in the Brazilian Amazon *

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Abstract

Climate change has increased the frequency of drought events in the Amazon. Deforestation worsens local climate dynamics, and weather shocks can, in turn, influence land-use decisions. In the Brazilian Amazon, where land tenure is a mix of public and private holdings, landholders on public lands may lack incentives to manage forests sustainably. This study examines how droughts differentially affect pasture expansion on public versus private lands. Using spatially matched comparisons within 0.5° grid cells, we find that during drought years, ranchers on public lands expand pasture area by 30% more than in baseline years, while private landholders show no significant response. We explore mechanisms behind this difference and find that drought-induced pasture degradation leads to expansion in both tenure types. However, ranchers on public lands expand pasture by 20% more than those on private lands in response to similar degradation. Moreover, only public landholders continue to expand even after controlling for degradation, suggesting additional drivers, such as lower deforestation costs in drier, more flammable forests. These findings indicate that climate-induced droughts increase deforestation pressure on public forests, which store substantial carbon stocks and cover over two-thirds of the Amazon. This vulnerability complicates efforts to mitigate climate change. Policymakers should enhance monitoring of public lands during drought years, improve enforcement of property rights, and consider taxing extensive cattle ranching. While our results highlight tenure-based differences under short-term drought conditions, they do not imply that one tenure system performs better in environmental measures under long-term aridification.

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1 Introduction

Climate change has increased the frequency and intensity of drought events in the Amazon, the largest rainforest in the world. The 2023-2024 drought recorded the lowest level of rainfall in 120 years of measurement, and several "once-in-a-century droughts" took place in the last few decades (Clarke et al. 2024). The rainforest is increasingly at risk of savannization as the region's climate shifts to drier conditions (Bottino et al. 2024).

Manmade deforestation can further deteriorate the region's climate, and weather conditions may also influence a farmer's decision to deforest. Using fire to deforest is a common practice in the area. Most deforestation occurs during the dry season when the forest is more flammable (Boucher, Roquemore, and Fitzhugh 2013). Moreover, the impact of droughts on deforestation through agricultural land-use change is complex and ambiguous (Desbureaux and Damania 2018). On the one hand, climate shocks reduce agricultural yields, thus reducing the profitability of agriculture, raising the value of outside options, and reducing deforestation pressure. On the other hand, drought-induced degradation may lead farmers to seek new cultivating areas, thus raising deforestation.

The Brazilian Amazon, which comprises 60% of the Amazon, is a mosaic of public and private lands. Considering that farmers in public lands are settled irregularly and may face eviction, farmers in both types of land may have very different incentives when managing their farmland. The effects of land tenure security on deforestation are also ambiguous and depend on the nature of the extractive process. Better tenure security provides incentives to invest in the land and make it productive, so if deforestation is capital incentive, better tenure security should lead to higher investment and deforestation. On the other hand, if deforestation is labor intensive and farmers in public lands see that land as a public good, they will not have incentives to invest in the land and manage their farms sustainably, thus increasing deforestation (Krishna et al. 2017; Walker et al. 2025).

Cattle ranching, the main driver of deforestation in the Amazon, is primarily an extensive activity in the region (Garrett et al. 2021). Pasture overgrazing is a common practice in a context where land is abundant and pasture restoration is costly. Ranchers often move to new lands instead of investing and renovating the pasture (Garrett et al. 2021). Ranchers in public lands, facing the possibility of eviction, have even fewer incentives to invest in the land and restore the pasture. By inducing pasture degradation, droughts may lead to a larger movement of ranchers in public lands abandoning their farms and seeking new land when compared to ranchers in private lands.

This study investigates how droughts affect farmers' land use decisions across public and private lands in the Brazilian Amazon. We investigate how these different climate and tenure security incentives interact to influence farmers' land use decisions. We focus on how cattle ranchers manage their pastureland due to the relevance of this activity for total deforestation and to compare similar deforestation sources across public and private lands. Using exogenous variation in the timing of drought years, we compare pasture expansion in private and public lands within 0.5° grid cells during drought years using cell and time-fixed effects.

Our findings provide significant evidence that ranchers on public lands accelerate their pasture expansion compared to those on private lands during drought years, supporting the theory that public land ranchers managing practices are less sustainable. Investigating the possible mechanisms behind this phenomenon, we find that droughts affect pasture degradation, which in turn affects pasture expansion. Ranchers in public lands are more sensitive to pasture degradation than private land farmers. This finding provides evidence that public land ranchers are less inclined to invest and restore their degraded pastureland and prefer to move to new land instead.

We also find that farmers in public lands still react to droughts after controlling for pasture degradation, which is evidence that other mechanisms are at play. One potential mechanism is that the environmental deregulation after 2012 incentivizes farmers in public lands to claim more land, and droughts make forest clearing easier. We find supporting evidence for this mechanism, but our data and methods do not allow us to identify it unequivocally.

This study contributes significantly to three branches of literature. A large branch of literature investigates the relationship between land tenure security and land use. Mendelsohn 1994 proposed a model that predicts that farmers with low tenure security would discount the future less and adopt less sustainable practices. Later works investigated this relationship in different contexts. Robinson, Holland, and Naughton-Treves 2014 perform a meta-analysis of the relationship between land tenure and tropical deforestation. The study finds that protected public lands display better conservation outcomes than private lands, but private lands outperform undesignated public lands, particularly in South America.

A related branch of literature investigates the relationship between agricultural efficiency and land use. Many studies investigate how increasing cattle stocking rates and restoring degraded pasture could help preserving and restoring native vegetation (Cohn et al. 2014; Spera 2017; Feltran-Barbieri and Féres 2021). We show that cattle intensification will remain a challenge as long as public land is readily available.

The literature on the impact of climate on land use choice is still nascent. A handful of studies have investigated the effects of droughts on deforestation in Africa, where subsistence agriculture dominates the rural landscape, finding that droughts increase deforestation (Desbureaux and Damania 2018; Leblois 2021; Vaglietti, Delacote, and Leblois 2022). These studies find that droughts are generally related to increased deforestation. Staal et al. 2020 investigates a drought and deforestation feedback mechanism in the Amazon and find that deforestation is responsible for 4% of the regional observed drying. The study also finds that deforestation responses to droughts vary, but it increases by an average of 0.13% in drought years.

We connect these branches of literature by investigating how climate shocks affect land-use responses across different land tenures. To the best of our knowledge, it is the first study to explore how the economic incentives generated by the interplay of climate and the different land tenures may result in significantly different land use responses. The findings also inform policymakers to increase public lands' monitoring during drought years, design mechanisms to better enforce public property rights, and impose a tax on extensive cattle ranching, as proposed by Cohn et al. 2014.

2 Background

The Amazon Basin is an exceptionally humid region that covers more than 40% of South America's land area and has a mean annual precipitation of 2300mm (Fisch, Marengo, and Nobre 2006). Rainfall is not equally distributed across the Amazon, however. The Southern portion of the Amazon receives less than 2000mm of rainfall, while the Northwestern portion of the Amazon, in the bordering region of Brazil, Colombia, and Venezuela, receives over 3000mm of rainfall, and there is no dry season in this region (Fisch, Marengo, and Nobre 2006; Michot et al. 2019). Nevertheless, most of the Amazon has marked rainy and dry seasons (Marengo 2004; NASA 2021; Skidmore 2023). The rainy season lasts from November to March, and the dry season from May to September, with August being the driest month (Fisch, Marengo, and Nobre 2006; NASA 2021). April and October are considered transition months (Fisch, Marengo, and Nobre 2006). The rainforest acts as a water recycling system and pumps humidity back into the atmosphere (NASA 2021). As a result, significant rainfall takes place even during the dry months (Bacellar 2022).

Despite the region being naturally humid, climate change has increased the frequency and intensity of drought events in the Amazon. The 2023-2024 drought recorded the lowest level of rainfall in 120 years of measurement, and several "once-in-a-century droughts" took place in the last few decades (Clarke et al. 2024). Different studies document increases in the duration of the dry season (Bottino et al. 2024). Droughts in the Amazon are also related to the El Niño Southern Oscillation (ENSO) phenomenon. The region suffered drier conditions during the ENSO years of 1983, 1995/1995, 1997/1998, 2005, 2010, 2015/2016 and 2023. Moreover, climate change is making extreme ENSO events more frequent (Skidmore 2023). The rainforest is increasingly at risk of savannization as the region's climate shifts to drier conditions (Bottino et al. 2024).

Local disturbances of the region's ecosystem also affect rainfall patterns. Deforestation affects the region's climate by altering the water cycle. Trees pump water from the soil into the air through their leaves, and this transpiration mechanism acts as an essential buffer during droughts (Staal et al. 2020). However, a feedback mechanism between climate and deforestation may exist, as the drivers of deforestation are also affected by climate shocks. Deforestation substantially increased in 2005, 2007, 2010, and 2015, and those years were marked by intense El Niño events, high air temperatures, or severe drought (Qin et al. 2023).

Droughts may affect land use change by lowering deforestation costs. In Brazil, fire is often used in the deforestation process. Fires do not occur naturally in the Amazon. As a humid rainforest, fires only occur during warm and dry conditions (Bottino et al. 2024). Deforestation usually occurs during the dry months, when the forest is easier to cut down and burn (Boucher, Roquemore, and Fitzhugh 2013). Droughts might amplify deforestation by making the vegetation more flammable and making it easier to use traditional slash-and-burn techniques. Furthermore, farmers often use fire to clear pasture of weeds, and dryer vegetation makes it easier for the fire to escape into nearby areas (Staal et al. 2020).

Another channel through which climate shocks may affect land use change is by affecting agricultural yields. Agriculture, a sector particularly vulnerable to climate shocks, relies on precipitation and temperature for production. Farmers may respond to droughts by altering land use, and the farmers' circumstances may alleviate or increase deforestation pressure (Mendelsohn 1994; Amacher, Koskela, and Ollikainen 2009; Robinson, Holland, and Naughton-Treves 2014; Balboni et al. 2023). On the one hand, considering the farmer has access to outside options, climate shocks reduce agricultural yields, thereby increasing the value of alternative options and alleviating deforestation pressure. On the other hand, farmers may attempt to expand their cropland or pasture to new areas to compensate for degradation caused by climate shocks, potentially leading to long-term land-use changes.

Pasture-fed cattle ranching is the agricultural activity that drives the most deforestation in the Brazilian Amazon. It is responsible for 90% of the total deforestation in the region (Mapbiomas 2024). Cattle ranching in the Amazon is characterized by extensive pasture management. Investments, such as irrigation and commercial inputs, including fertilizers and lime, are uncommon (Garrett et al. 2021). These extensive practices lead to across-the-board pasture degradation due to inadequate land use and management of vegetation or livestock, which often results from overgrazing, lack of fertilization, and pest control (Feltran-Barbieri and Féres 2021). Since reverting this degradation requires considerable investments, ranchers often move to newly deforested land (Garrett et al. 2021). As a result, ranchers depend heavily on rainfall, and this extensive production system leaves farmers particularly vulnerable to climate shocks.

The last piece of information that completes our study's puzzle is land tenure in the Brazilian Amazon. A mosaic of public and private lands, the region has a long history of insecure land tenure in which land grabbers and squatters often occupy public land (Azevedo-Ramos et al. 2020). Public lands are mainly divided into conservation units, indigenous lands, and undesignated public forests. Some conservation units may allow sustainable agricultural production, but others strictly forbid economic activities. Undesignated public forests are not protected and are especially vulnerable to occupation.

Deforestation in public lands is one of the most pressing problems in the Amazon. Between 2019 and 2021, 51% of the total deforestation occurred in indigenous lands, units of conservation, and undesignated public forests. In a context of poor enforcement and high political pressure, landgrabbers often have had their occupied lands grandfathered in by the Brazilian Congress. The Forest Code reform of 2012 legalized all public lands occupied until 2008. Nonetheless, the Brazilian Federal Police often arrest landgrabbers (Polícia Federal em Rondônia 2024).

3 Conceptual Model

Understanding how land tenure conditions shape ranchers' responses to climate shocks requires a framework that explicitly incorporates the risk environment faced by farmers in the Amazon. The Brazilian Amazon is characterized by a mosaic of private and public lands, where the latter include conservation units, Indigenous territories, and vast expanses of undesignated public forests (UPFs). In these public lands, ranchers often occupy irregularly and face persistent legal and extralegal threats to their tenure security. Federal law prohibits the privatization of these forests, yet enforcement is uneven, and waves of amnesties and titling initiatives have blurred the boundaries between licit and illicit claims (Carrero et al. 2022).

To formalize these dynamics, we model a farmer's land use as an asset-replacement problem. Farmers are assumed to graze cattle on a single parcel that degrades over time, and this parcel can be "replaced" by clearing a fresh plot of land. Each season, the farmer observes the quality of the land, which is a function of time and drought spells, and then chooses to continue grazing on the current piece of land or to replace the land and clear a new plot.

3.1 Dynamics

Formally, let $d \in \{0, 1\}$ denote a farmer's binary decision to replace the land. Land quality $q \in [0, \bar{q}]$ is an endogenous state variable and is assumed to decrease over time. Land quality is negatively impacted by drought spells $z \in \{0, 1\}$, an exogenous state variable that follows a stationary Markov process. Land quality in period t can be expressed using the state equation:

$$q_t = \begin{cases} g(q_{t-1}, z_t) & \text{if } d_t = 0, \\ \bar{q} & \text{if } d_t = 1. \end{cases}$$

That is, current land quality q_t depends on last period's land quality and whether there is a drought spell in the current period. The condition $0 < g_q < 1$ ensures that land quality is decreasing over time, and $g(q, 1) < g(q, 0)$ implies land quality is negatively impacted by drought. If a farmer replaces the parcel, land quality "resets" to its maximum $\bar{q}$.

Let's consider a farmer's utility $u(q, d)$ as a function of grazing profits $\pi(q)$, which are assumed to be increasing and concave in land quality, and depends on replacement costs:

$$u(q, d) = \begin{cases} \pi(q) & \text{if } d = 0, \\ \pi(\bar{q}) - \rho - f(z) & \text{if } d = 1. \end{cases}$$

Here, ρ represents the rental rate (shadow price of land) and $f(z)$ represents the cost of clearing new land, assumed to decrease in drought spells: $f(1) < f(0)$. Each season, the farmer observes (q_t, z_t) and makes a land-use decision to maximize expected net present utility $V(q, z)$, represented with the Bellman equation:

$$V(q, z) = \max \left\{ u(q, 0) + \beta \mathbb{E}_{z'} V(g(q, z'), z'),\ u(\bar{q}, 1) + \beta \mathbb{E}_{z'} V(g(\bar{q}, z'), z') \right\},$$

where $\beta < 1$ denotes the discount factor. The Bellman equation says that the farmer must compare the benefit of waiting to replace the land with the benefit of replacing the land, where these benefits consist of present-day utility and the expected future benefits of all future land use.

Consider now a farmer's policy function $d^*(q, z)$, which describes their optimal land replacement decision, given a land quality of q and a drought spell of z. Define the "advantage-of-waiting" as:

$$\Delta(q,z) = \underbrace{\left[\pi(q) + \beta \mathbb{E}_{z'} V\left(g\left(q,z'\right),z'\right)\right]}_{\text{Wait}} - \underbrace{\left[\pi(\bar{q}) - \rho - f(z) + \beta \mathbb{E}_{z'} V\left(g\left(\bar{q},z'\right),z'\right)\right]}_{\text{Replace}}$$
$$= \underbrace{\pi(q) - \left[\pi(\bar{q}) - \rho - f(z)\right]}_{\text{Present advantage of waiting}} - \underbrace{\beta\left[\mathbb{E}_{z'} V\left(g\left(\bar{q},z'\right),z'\right) - \mathbb{E}_{z'} V\left(g\left(q,z'\right),z'\right)\right]}_{\text{Future disadvantage of waiting}}$$

The advantage-of-waiting function sufficiently describes a farmer's policy function: as long as $\Delta(q,z) > 0$, i.e., the benefits to waiting are larger than the benefits of replacing, a farmer will wait to replace their land. This can be decomposed into a present advantage of waiting and a future disadvantage of waiting. The present advantage compares the benefits of the current degraded land $\pi(q)$ to those the would receive from undegraded land $\pi(\bar{q})$ net of clearing costs $\rho + f(z)$. For high values of land quality, the present advantage will be positive and will decrease over time as the land degrades. The future disadvantage of waiting is the relative future benefit of starting the next period with less degraded land if the farmer replaces the current land. Note that $V(g(\bar{q},z'),z') - \mathbb{E}_{z'} \geq V(g(q,z'),z')]$ since $\bar{q} \geq q$; thus, the future disadvantage of waiting is weakly positive and becomes greater over time as the land degrades. Thus, the present advantage of waiting must be large enough to offset the future disadvantage of waiting in order to delay replacing the land.

The policy function can be completely described by a threshold rule using the advantage-of-waiting function, $\Delta(q,z)$. Since $\pi(q)$ is assumed to be strictly increasing in land quality q and the cost of clearing $\rho + f(z)$ does not depend on land quality, then the value function $V(q,z)$ is strictly increasing in q, and thus, $V(g(q,z'),z')$ is strictly increasing in q. As a result, $\Delta(q,z)$ is strictly increasing in q and there exists a threshold land quality $q^*(z)$ such that we can define the farmer's policy function as:

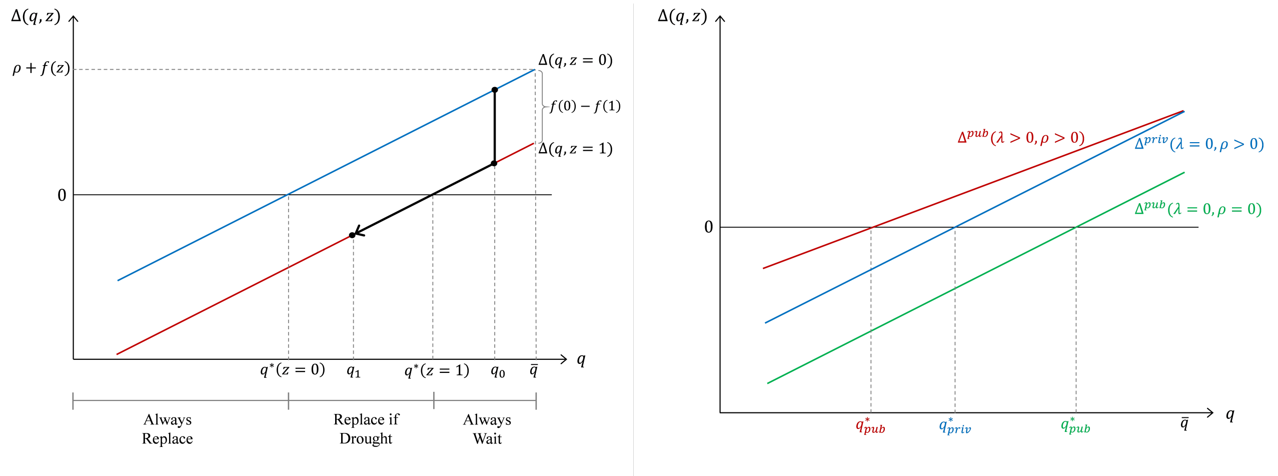
$$d^*(q,z) = \begin{cases} 0 & \text{if } q > q^*(z) \quad (\text{Wait}), \\ 1 & \text{if } q \leq q^*(z) \quad (\text{Replace}), \end{cases}$$

The threshold $q^*(z)$ marks the value of the land quality below which a farmer chooses to replace their land. Higher values of $q^*(z)$ represent land replacement at younger ages and with less degradation, meaning a higher rate of pasture expansion for any given drought conditions z. Larger differences in $q^*(z)$ across drought conditions, $q^*(1) - q^*(0)$, represent a larger set of land quality values that are subject to replacement with a drought, thereby representing a larger pasture expansion in response to a drought.

3.2 Tenure differences and drought effects

We can now use this theoretical framework to depict the effect that droughts and land tenure, individually, have on a farmer's land-use choice, and, finally, use our model to predict how droughts and land tenure interactions affect land-use decisions.

Let us first analyze the effects of droughts on a generic farmer's decisions. Drought affects the farmer's calculus in two ways, as illustrated in Figure 1 (a) (notice that the advantage-of-waiting curve, $\Delta(q, z)$, is upward sloping). First, it induces a "curve shift" by reducing the cost associated with replacing the current parcel of land with a new one. This can be represented by a downward shift in $\Delta(q, z)$ by $f(0) - f(1)$, and results in an increase in the quality threshold q^*. Thus, for land with quality $q(0) < q < q(1)$, a drought induces land replacement (i.e., pasture expansion) by decreasing the cost of replacement.



(a) Impacts of droughts on land replacement

(b) Private versus public land conversion

Fig. 1

Second, drought induces a "state shift" by negatively affecting the quality of land itself, and thus, the profits associated with waiting. This can be seen in the movement from q_0, the quality of land without drought ($z = 0$), to q_1, the quality of land with drought ($z = 1$). Thus, any land quality that is pushed over the threshold $q^*(1)$ by droughts will be replaced by the farmer. Both mechanisms, therefore, lead to a reduction in the advantage of waiting and thus increase pasture expansion.

Let us now examine the impact of different land tenure systems on land use. We can adjust two parameters to differentiate public from private land use.

First, the parameter β represents the discount factor associated with a risk-free discount rate. Suppose a farmer on public land faces some probability of being evicted. Assuming that the probability of eviction is memoryless and is independent of land quality, then we can represent a public farmer's discount factor as $\beta(1 - \lambda)$, where $0 < \lambda < 1$ is the constant hazard of being evicted.

The motivation for the eviction hazard constant λ is rooted in Brazil's contemporary land-tenure realities. Farmers on public lands are subject to state enforcement risks such as fines, embargoes, and the confiscation of means of production (Moutinho and Azevedo-Ramos 2023). They also face violent disputes with other claimants, which have historically resulted in threats, forced displacements, and even assassinations (A. Sant'Anna and Young 2010; Carrero et al. 2022). Other documented sources of tenure insecurity on public lands include the risk of arrest by state law enforcement and the reduced marketability of properties with contested or fraudulent titles[1].

Second, the parameter ρ represents the opportunity cost of converting forested land to pasture. For private land owners with scarce land, we can think of $\rho > 0$, either due to the shadow value of land that is already owned by the farmer, or the rental/purchase price of land on the private market. For public land users, expanding into public forest has no such opportunity cost, and thus, $\rho = 0$.

We are now in a position to conduct some comparative statics to see how land use differs across private and public land. The comparative statics for a given drought spell z are depicted in Figure 1 (b). With a positive probability of being evicted, public farmers have a smaller discount factor. This has the effect of rotating $\Delta(q, z)$ up around the point at $\bar{q}$, illustrating that the advantage of waiting for public farmers is higher than for private farmers for all $q < \bar{q}$ because they discount more the future disadvantage of waiting. Thus, $q^*_{pub}(z) < q^*_{priv}(z)$. In other words, public farmers are less likely to incur a costly investment in land clearing if there is some probability that they will be evicted and unable to reap the rewards. Thus, the probability of eviction incentivizes public farmers to hold onto land longer than private farmers, allowing the land to degrade more. Private farmers, on the other hand, are more likely to replace land and expand pasture, all else equal.

In contrast, with no opportunity cost associated with land $\rho = 0$, public farmers have a constant lower advantage of waiting than private farmers, regardless of the land quality. This has the effect of shifting $\Delta(q, z)$ down in a parallel fashion. As a result, $q^*_{pub}(z) > q^*_{priv}(z)$: the relative ease of converting new land into pasture incentivizes public farmers to hold on to land for shorter periods of time and expand pasture at greater rates than private farmers. Overall, whether public farmers expand pasture at greater rates than private farmers depends on whether the "opportunity-cost-of-land" effect dominates the "probability-of-getting-evicted" effect.

Based on these results, we can finally analyze the differential drought effects across public and private farmers. Figure 2 depicts the comparative statics predictions, assuming that private and public farmers have the same baseline pasture conversion rates, $q^*_{pub}(0) = q^*_{priv}(0)$, for simplicity.

[1]The appendix provides news sources illustrating: (1) arrests of land grabbers by federal police, (2) the classification of properties with disputed or fraudulent titles as "distressed assets" in the land market, and (3) violent disputes among competing claimants.

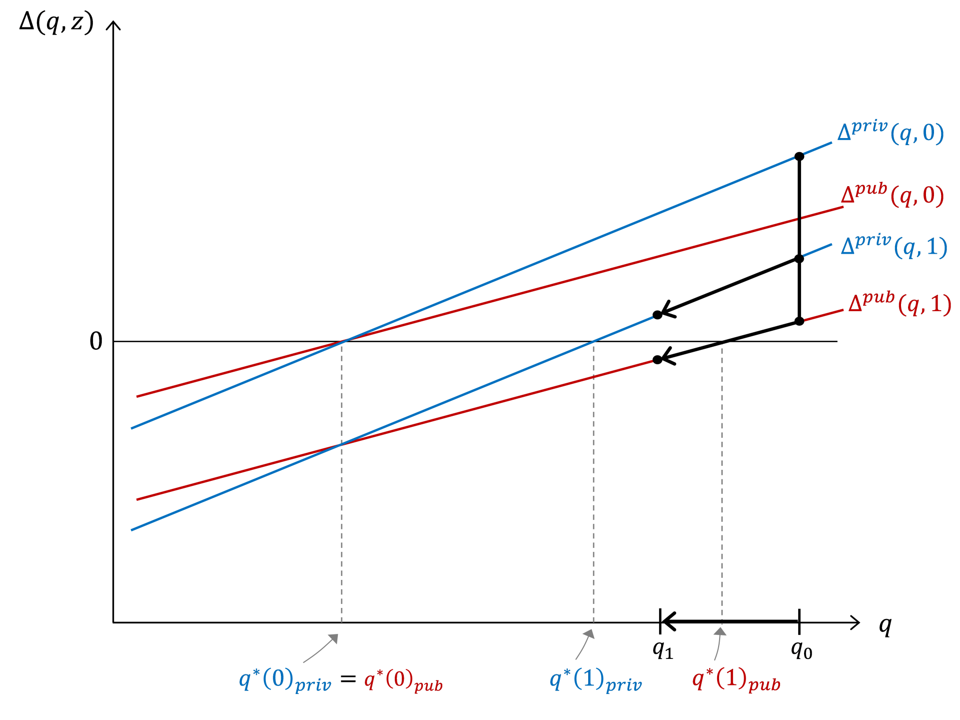


Fig. 2: Drought effects: Public vs. Private

First, the drought-induced "curve-shift" effect from reducing the clearing cost of land shifts the advantage-of-waiting curve down. This "curve-shift" effect is represented in 2 by the difference between $q^*(1)_{priv}$ and $q^*(0)_{priv}$ for private lands, and the difference between $q^*(1)_{pub}$ and $q^*(0)_{pub}$ for public lands. Since public and private farmers experience the same reduction in land-clearing costs, $\Delta(q,z)$ shifts down vertically by the same amount for both types of farmers. However, $\Delta(q,z)$ is flatter for public farmers since they discount the future disadvantage of waiting more than private farmers, resulting in a larger horizontal shift in $\Delta(q,z)$ for public farmers. Thus, $q^*(1)_{pub} - q^*(0_{pub}) > q^*(1)_{priv} - q^*(0)_{priv}$: more land will be replaced by public farmers than private farmers in response to the drought, regardless of the baseline pasture conversion rates. The reduction in deforestation costs during droughts matters relatively more for farmers on public lands, because the risk of eviction makes them reluctant to invest in costly clearing methods that might not yield returns. By reducing the investment cost, droughts shift the balance between the "opportunity-cost-of-land" effect and the "probability-of-getting-evicted" effect towards the former, and therefore, public land farmers react more to droughts.

Second, the "state-shift" effect reduces the quality of land itself. Land quality that is pushed over the threshold $q^*(1)$ by drought will be replaced by the farmer. This is depicted in Figure 2 by the movement from $q^*(0)$, the quality of land without the drought, to $q^*(1)$, the quality of land with the drought. As depicted, the drought induces enough degradation in land quality to justify replacing the land for the public farmer, but not the private farmer. Note that while the curve shift effect is determined by the slope of $\Delta(q, z)$, the size of the state-shift effect will be the same for both public and private farmers: any land quality q that lies within $q(0) - q(1)$ of the threshold $q^*(1)$ will be induced to being replaced. Thus, as long as droughts are assumed to affect land quality equally across land types, the "state-shift" effect will be the same.

Overall, the model underscores that differences in land tenure regimes critically mediate farmers' responses to drought. In the absence of climatic shocks, relative rates of pasture expansion on private versus public lands depend on whether the higher opportunity cost of waiting (which encourages more expansion by private farmers) outweighs the higher opportunity cost of conversion (which restrains it). Droughts, however, introduce additional forces that shift this balance. The "curve-shift" effect, operating through reductions in clearing costs, induces a larger response on public lands, where tenure insecurity typically discourages costly long-term investments. By contrast, the "state-shift" effect, operating through reductions in land quality, generates symmetric responses across tenure types as long as drought-induced degradation is uniform. Taken together, these mechanisms imply that droughts systematically amplify pasture expansion on public relative to private lands, even when baseline expansion rates differ, thereby highlighting how climate shocks and tenure insecurity interact to shape land-use dynamics.

Our simple model highlights the interaction of land tenure and climate shocks in shaping land-use responses, but it omits other relevant dynamics. One important example is investment in pasture restoration. Because farmers on public lands face weaker incentives to undertake costly, long-term improvements, they are less likely to restore degraded pasture. A higher eviction hazard (λ) further discourages such investments, as the risk of losing access to the land reduces the expected returns from long-term restoration. When drought reduces the cost of clearing new land, these farmers may therefore favor expansion into previously uncleared areas rather than investing in restoration.

3.3 Intensive and Extensive Pasture Growth

In the last section, we suppose we could observe an individual rancher's land plot and the farmer's pasture growth response to climate shocks. Unfortunately, that often is not the case. One practical challenge of this paper is that we do not observe the boundaries of public land farms since these ranchers are settled irregularly. To get around this obstacle, we must impose assumptions that do not come without a cost.

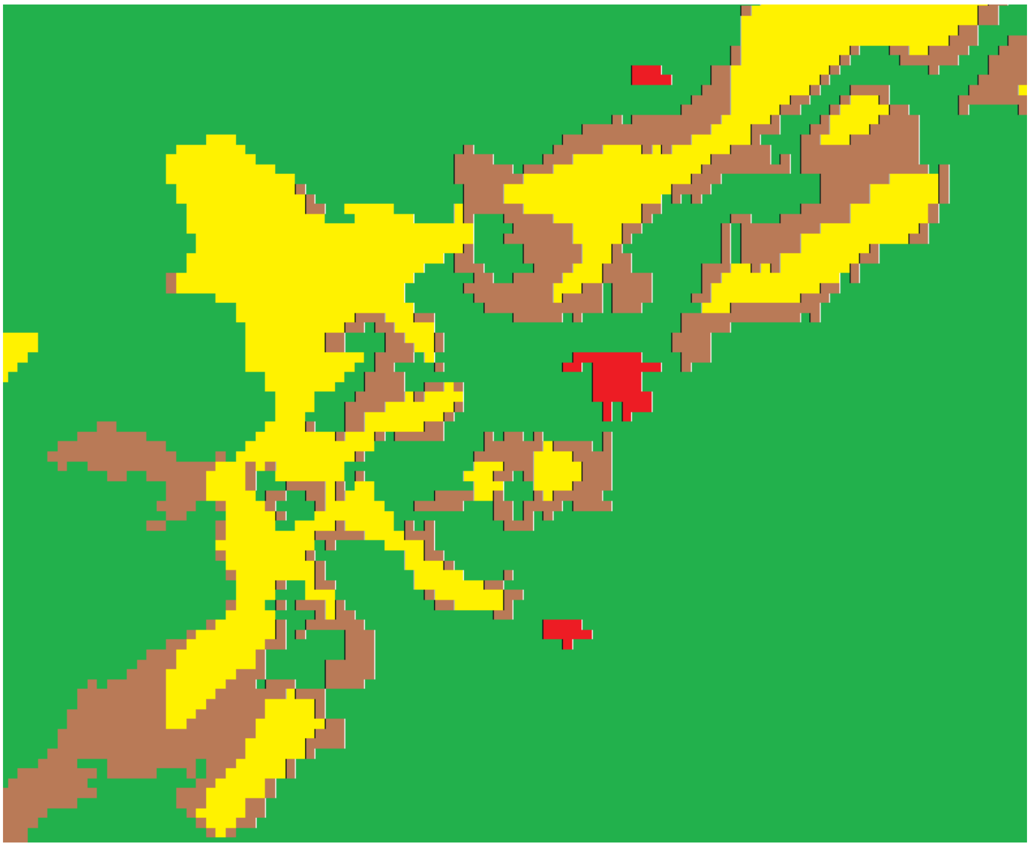
To motivate this discussion, suppose we observe two ranchers, i and j. Rancher i is settled in private lands, and Rancher j in public lands. Suppose we also observe their land plots in years t and $t+1$ and suppose the ranchers expand their pasture land from year t to $t+1$. We call this growth in the ranchers' pasture *intensive* pasture growth. Ideally, we would like to compare both ranchers' intensive pasture growth.

Suppose now that we observe, close to rancher's k land, a newcomer rancher k in year $t+1$. Rancher k was not settled in the area during year t and decided to create a new ranch on previously unoccupied public land in year $t+1$. This pasture growth that comes from rancher k's new activity we call *extensive* pasture growth.

The primary goal of this paper is to investigate how ranchers on public lands react differently to drought shocks compared to ranchers on private lands. It is important to note that this problem involves ranchers already settled in public lands when the drought hits, as farmer j; it does not involve the problem of public land invasion by landgrabbers, as farmer l. As we cannot observe well-defined properties in public lands, we cannot directly observe ranchers j and l. That is, we cannot directly observe intensive and extensive growth in public lands. Therefore, we cannot use public and private farms as our unit of analysis and compare the land-use change across farms of different land tenures.

However, we observe land tenure, that is, whether a given area is public or private land, and we also observe land use. Let us define the observed intensive and extensive pasture growths using these two pieces of information. Define observed intensive growth in year t, $\widehat{IG}_t$, as the growth in pasture that intersects pastureland in year $t-1$, and extensive growth in year t, $\widehat{EG}_t$, as the growth in pastureland that does not intersect with pastureland in year $t-1$. Figure 3 represents observed intensive and extensive pasture growth. Yellow represents pasture in year $t-1$, brown represents observed intensive pasture growth in year t, and red represents observed extensive pasture growth in year t.

Fig. 3: Observed Intensive and Extensive Pasture Growth



Based on these definitions, let us define the following two estimators of intensive pasture growth:

$$\widehat{PGint}_{ts} = 1(s = pub) \cdot (\widehat{IG}_{ts}) + 1(s = priv) \cdot (\widehat{IG}_{ts} + \widehat{EG}_{ts}) \tag{1}$$

$$\widehat{PGtot}_{ts} = 1(s = pub) \cdot (\widehat{IG}_{ts} + \widehat{EG}_{ts}) + 1(s = priv) \cdot (\widehat{IG}_{ts} + \widehat{EG}_{ts}) \tag{2}$$

where s indicates if the land tenure is public or private.

The variable $\widehat{PGint}_{ts}$ considers only the observed intensive growth as the actual intensive growth in public lands. Assuming all private lands are already settled, all pasture growth in these lands is intensive growth. For private lands, both observed intensive and extensive growth are considered the actual intensive growth. The underlying assumption is that all observed extensive growth in public lands comes from new ranchers invading public lands.

Analogously, the variable $\widehat{PGtot}_{ts}$ considers that all observed growth is intensive for both land tenures. The underlying assumption in this case is that the number of ranchers in public lands is fixed, and there are no newcomers. The assumption for private lands is the same as before.

Finally, considering that we want to use $\widehat{PGint}_{ts}$ and $\widehat{PGtot}_{ts}$ to estimate the impacts of droughts on intensive public and private pasture growth, it is important to understand the implications for our estimations when the assumptions above are not met. More precisely, we would like to use these variables to estimate the impacts of droughts on the pasture growth difference between public and private lands. Keeping the assumption that all growth in private lands is intensive, we assume all growth in private lands is estimated correctly since these variables capture the same growth in private lands. Let us now consider three cases for public lands: all observed extensive growth is extensive, all observed extensive growth is intensive, and finally, some but not all observed extensive growth is intensive. Let us also consider b_{pub}, b_{priv}, and b_{EG} the effect of droughts on intensive public land pasture growth, private land pasture growth, and extensive public land pasture growth, respectively. We analyze how changing these three assumptions affects the estimation of b_{pub} and $b_{priv} - b_{pub}$ if we use $\widehat{PGint}_{ts}$ and $\widehat{PGtot}_{ts}$ as our pasture growth variables.

Let us consider the first case. If all observed extensive growth is extensive, then the variable $\widehat{PGint}_{ts}$ precisely captures the intensive pasture growth on public lands. Therefore, b_{pub} and $b_{priv} - b_{pub}$ are precisely estimated since these different assumptions do not affect the estimation of b_{priv}.

However, in this case, $\widehat{PGtot}_{ts}$ includes as intensive growth in public lands some extensive growth. The implications for the estimation bias of b_{pub} depend on the signs of b_{pub} and b_{EG}, and the bias of $b_{priv} - b_{pub}$ depend on the signs of b_{pub} and b_{EG}, and also whether $b_{priv} > b_{pub}$ or $b_{priv} < b_{pub}$. Consider b^*_{pub} and $b_{*priv-b*_{pub}}$ the respective estimator of each coefficient. The bias in each one of these cases is summarized on the right-hand side of table 1. First, consider that both b_{pub} and b_{EG} are negative. Since $\widehat{PGtot}_{ts}$ adds the extensive growth to the intensive growth, both negative effects compound, and the negative effect of droughts on intensive public land pasture is overestimated, i.e., $b^*_{pub} < b_{pub} < 0$. In this case, if $b_{priv} > b_{pub}$, then $b_{priv} - b^*_{pub} > b_{priv} - b_{pub} > 0$ and our estimator overestimates the positive difference between private and public land pasture growth. However, if $b_{priv} < b_{pub}$, then $b_{priv} - b_{pub} < b_{priv} - b^*_{pub} < 0$, and our estimator underestimates the negative difference between private and public growth.

Consider now that b_{pub} is negative, but b_{EG} is positive. Since $\widehat{PGint}_{ts}$ includes extensive pasture growth in its composition, b_{EG} reduces b_{pub} negative effect and b^*_{pub} is underestimated. If $b_{priv} > b_{pub}$, then $b_{priv} - b_{pub} > b_{priv} - b^*_{pub} > 0$ and our estimator underestimates the positive difference between private and public land pasture growth. However, if $b_{priv} < b_{pub}$, then $b_{priv} - b_{*pub<b_{priv}-b_{pub}<0}$, and our estimator overestimates the negative difference between private and public growth.

We can apply the same logic to the other cases. If $b_{pub} > 0$ and $b_{EG} \leq 0$, b^*_{pub} is underestimated and $b^*_{priv} - b^*_{pub}$ is overestimated and underestimated if $b_{priv} > b_{pub}$ and $b_{priv} < b_{pub}$, respectively. If $b_{pub} > 0$ and $b_{EG} > 0$, then b^*_{pub} is overestimated. Now, $b^*_{priv} - b^*_{pub}$ will be underestimated if $b_{priv} > b_{pub}$ and overestimated if $b_{priv} < b_{pub}$.

Tab. 1: Intensive pasture growth estimators and estimation bias

		$\widehat{PGint}$ if $\alpha > 0$					$\widehat{PGtot}$ if $\alpha < 1$		
		b^*_{pub}	$b^*_{priv} - b^*_{pub}$				b^*_{pub}	$b^*_{priv} - b^*_{pub}$	
			$b_{priv} > b_{pub}$	$b_{priv} < b_{pub}$				$b_{priv} > b_{pub}$	$b_{priv} < b_{pub}$
b_{pub}	< 0	U-	U +	O-	b_{EG}	< 0	O-	O+	U-
						≥ 0	U-	U +	O-
b_{pub}	> 0	U +	O +	U-	b_{EG}	≤ 0	U +	O+	U-
						> 0	O+	U +	O-

U represents an underestimated coefficient and O represents an overestimated coefficient. The signs represent whether the coefficient is positive or negative, ie, U- represents an underestimation of a negative coefficient, and O+ represents an overestimation of a positive coefficient

Let us now consider the second case in which all observed extensive growth is actually intensive growth. Now, the variable $\widehat{PGtot_{ts}}$ precisely captures all the intensive growth, and the estimators derived from it should be unbiased. However, now $\widehat{PGint_{ts}}$ fails to consider the change in intensive pasture growth that we observe as extensive. Therefore, b^*_{pub} will underestimate b_{pub} regardless of the sign. The bias in this case is summarized on the left-hand side of table 1.

The bias of $b^*_{priv} - b^*_{pub}$ depends on the sign of b_{pub} and whether $b_{priv} > b_{pub}$ or $b_{priv} < b_{pub}$. If $b_{pub} < 0$ and $b_{priv} > b_{pub}$, then $0 < b_{priv} - b^*_{pub} < b_{priv} - b_{pub}$, and $b^*_{priv} - b^*_{pub}$ is underestimated. If $b_{priv} < b_{pub}$, then $b_{priv} - b^*_{pub} < b_{priv} - b_{pub} < 0$ and $b^*_{priv} - b^*_{pub}$ is overestimated. Analogously, $b^*_{priv} - b^*_{pub}$ will be overestimatedif $b_{priv} < b_{pub}$ and underestimated if $b_{priv} > b_{pub}$, considering that $b_{pub} > 0$.

Finally, considering that a fraction , $0 << 1$, of all observed extensive pasture growth in public lands is actually intensive growth, then both variables fail to capture the correct intensive growth. The same cases discussed before apply and the bias is summarized in table 1. In sum, the estimators derived from $\widehat{PGint_{ts}}$ and $\widehat{PGtot_{ts}}$ can both simultaneously underestimate or overestimate the actual effects b^*_{pub} and $b^*_{priv} - b^*_{pub}$, therefore, together they do not represent upper and lower bounds. The estimator derived from $\widehat{PGint_{ts}}$ will always underestimate b^*_{pub} if $\alpha > 0$, and the estimator derived from $\widehat{PGtot_{ts}}$ may overestimate or underestimate it depending on the sign of b_{EG}. The bias of $b^*_{priv} - b^*_{pub}$ depend on whether $b_{priv} < b_{pub}$, and on the sign of b_{EG} in the case of $\widehat{PGtot_{ts}}$. Ultimately, comparing the sign and magnitude of b^*_{pub} and $b^*_{priv} - b^*_{pub}$ derived from both variables helps us shed light on which case is more likely to be accurate.

Regardless of the assumptions, the variable $\widehat{PGtot_{ts}}$ captures the overall difference in pasture growth across public and private lands. It may shed light on how each type of tenure incentivizes land use conversion regardless of the type and number of farmers in each type of land. Even though this last variable may not perfectly capture how farmers settled in both types of land respond to climate shocks, it may still contribute to important policy implications.

4 Empirical Strategy

To test the hypothesis that farmers in public lands manage their properties less sustainably when a drought hits, let us define 0.5° grid cells as our unit of analysis. We compare how farmers in public and private lands within the same cell respond to droughts using the following model:

$$y_{cit} = \beta_0 + \beta_1 Dry_{ct} + \beta_2 Priv_{ci} + \beta_3 Dry_{ct} * Priv_{ci} + \gamma_c + \delta_t + \varepsilon_{cit} \tag{3}$$

where y_{cit} is the outcome variable in cell c, year t, and tenure i, Dry_{ct} is a dummy variable that equals to one if the drought index is below one standard deviation in cell c in year t, and $Priv_{ci}$ is a dummy variable that equals to one if land tenure i in cell t is private. Cell and time-fixed effects are represented by γ_c and δ_t, respectively. Using variable Dry_{ct} as a standard deviation within the cell's c climate, we estimate whether drought shocks in year t, considering the cell's t usual climate, induce pasture expansion in public and private lands.

We use two outcome variables. The first variable is the difference in logs of pastureland area in years t and $t-1$ when we consider only the observed intensive growth in public lands. This variable corresponds to an approximate percentual version of $\widehat{PGint_{ts}}$ defined in the previous section. Analogously, the second outcome variable corresponds to an approximate percentual version of $\widehat{PGtot_{ts}}$ and is the difference in logs of pastureland area in years t and $t-1$ when we consider the total growth for both land tenure types.

Our coefficients of interest are β_1 and β_3. The coefficient β_1 tells us how farmers generally respond to drought years. More importantly, β_3 tells us how farmers in private lands respond differently to droughts compared to public land farmers. Therefore, public land farmers response to droughts is captured by β_1, and private land farmers, $\beta_1 + \beta_3$. The constant β_0 captures public farmers' behavior in non-drought years, while $\beta_0 + \beta_2$ captures private farmers' behavior in those years.

The cell fixed effects control for everything common to private and public farms in the same cell. In essence, it allows us to compare how differently public farmers react to droughts compared to private farmers within the same cell. We exploit exogenous variation in weather. For our coefficients to causally identify the impacts of droughts on public and private pasture expansion, there must be no time-varying unobserved variables correlated with the difference between public and private pasture expansion and droughts. In other words, this assumption will be violated if there are any trends in the difference between public and private pasture expansion somehow correlated with droughts.

Considering that cells have different compositions of pasture and forests within their public and private lands, we want to compare how pasture growth responds to dry conditions in cells with a similar composition of pasture and forest across different land tenures. Therefore, we give greater weight to cells with similar public and private land cover composition. Let $p_{pub} = \frac{pasture}{pasture+forest}$ in public lands, and $p_{priv} = \frac{pasture}{pasture+forest}$ in private lands. Our weights take the form $1 - |p_{pub} - p_{priv}|$, thus giving more weight to more balanced cells.

We trimmed our sample to include observations with more than one square kilometer of pasture in 2001 to avoid bias from percentage changes in places with small baseline pastureland. Similarly, we only include observations with at least 10% of forest cover in 2001. We use Conley spatial standard errors with the code made available by Hsiang 2010.

5 Data

In this study, we use the SPEI drought index. The SPEI is a relative measure based on the reference period's water balance and indicates water surpluses or deficits. It is calculated based on the water balance between the monthly precipitation and potential evapotranspiration. The SPEI is a relative measure based on the reference period's water balance and indicates water surpluses (positive values) for deficits (negative values). It represents the number of standard deviations from the normally accumulated climatic water balance for the respective location and time of the year. The data is available at the 0.5° level. Our analysis considers the average drought conditions from January to December. We also explore seasonal drought conditions when investigating the possible mechanisms of droughts and differential pasture expansion. [2]

Land use data comes from the Mapbiomas dataset. Mapbiomas uses Landsat satellite images and machine learning algorithms to classify pictures into land uses, including pasture. They use many variables collected from the images to feed the machine-learning model, including spectral color bands and indices of vegetation moisture. For pasture specifically, they only use data from the wet season for the prediction, as pasture is vulnerable to climate conditions. In the Amazon, this class may occur in recently deforested areas, even if farming activities have not started yet. Areas of natural pasture are predominantly classified as grassland or wetland, separated from manmade

[2] The SPEI index compares the drought conditions in a given number of months to the historical average drought conditions over those months. For instance, SPEI-3 May 2009 compares the drought conditions from March to May 2009 to the historical average drought conditions for those months. The primary drought variable we use in this paper is SPEI-12 December.

pasture. Mapbiomas also create data about the quality of the pasture. The pasture is classified into healthy, moderately, or severely degraded based on normalized vegetation moisture information. The data is available at a refined spatial resolution of 30m x 30m.

Land tenure data comes from the Atlas of Brazilian Agriculture. This dataset, created from a methodology described by Sparovek et al. 2019, integrates public datasets of land tenure from different sources and removes spatial overlaps. Therefore, it can be considered a snapshot of Brazilian land tenure as of 2019. It deals with overlaps using a hierarchical model that classifies the land tenures based on a priority system. For instance, private land under CAR, an environmental land registry program, has less priority than indigenous land because indigenous rights are established in the Brazilian Constitution.

In 2012, the Brazilian government created a new system for property registration called the Rural Environmental Registry (CAR). It was developed to facilitate the environmental regulation of rural properties since many did not comply with Brazil's forest legislation (Garrett et al. 2021). It consists of a self-declaratory registry where landowners input their farms' geolocated boundaries into the system, as well as the location of the farm's forest reserve. It is a system that monitors whether landowners comply with the forest code and does not grant land ownership. However, the system generates a receipt that the land was registered, giving land grabbers some credibility to their land claims in the context of ill-defined property rights.

The Atlas of Brazilian Agriculture considers two types of lands registered in CAR. "CAR premium" consists of properties that are likely to be legitimate private lands and have less than 5% of their area overlapped with other properties. "CAR poor", in turn, are properties registered in CAR with more than 5% of their area overlapped with other properties. Those properties are likely to be invaded public lands. We removed CAR-poor lands from our analysis to better distinguish between public and private lands. Later, we conduct robustness tests reincluding those lands in our analysis.

5.1 Descriptive Statistics

Table 7 below presents the descriptive statistics considering the years between 2003 and 2021. On average, cells were under droughts 28% of the time, and 65% of the land area considered is public. We can observe that the growth in pasture is larger in private lands when we consider just the observed intensive growth in public lands, but it is larger in public lands when we consider the total growth in those lands. On average, private lands have a higher percentage of pastureland than public lands. The former has a 20% rate of pasture saturation, as opposed to 12% in the latter.

Tab. 2: Basic Summary Statistics

	Mean	SD	Min	Max	N
Dry	0.2840	0.4509	0.00	1.00	50620
Share of Public Lands	0.6555	0.3259	0.00	1.00	50620
Pasture Growth (int)	0.0218	0.1100	-1.14	3.50	50600
Private Pasture Growth	0.0276	0.1214	-1.13	3.50	22580
Public Pasture Growth (int)	0.0171	0.0996	-1.14	1.85	28020
Pasture Growth (tot)	0.0349	0.1374	-1.13	4.36	50600
Public Pasture Growth (tot)	0.0408	0.1488	-1.13	4.36	28020
Pasture Saturation	0.1554	0.2379	0.00	1.00	50600
Private Pasture Saturation	0.1985	0.2457	0.00	1.00	22580
Public Pasture Saturation	0.1206	0.2254	0.00	1.00	28020
Pasture Growth From Forest	0.8690	0.2288	0.00	1.00	39885

Pasture Growth (int) corrresponds to $\widehat{PGint\_ts}$. Pasture Growth (tot) corrresponds to $\widehat{PGint\_tot}$

Figure 4 shows the average occurrence of droughts from 2003 to 2022 over our studied area. We can observe a higher drought rate in the southern and western portions of the map. Figure 5, in turn, shows the average difference between public and private pasture growth rates over the studied period, considering only the observed intensive growth for public lands. Green cells observed more public land pasture growth, and pink cells observed more private land pasture growth. Generally, average private land pasture growth is more concentrated in the northern portion of the map, where average drought conditions were milder.

6 Results

The main results are presented in figure 6. We find evidence of a positive impact of droughts on public pasture expansion, whereas we find no evidence of changes in pasture expansion on private lands. These results are robust across both variables, $\widehat{PGint}_{ts}$ and $\widehat{PGtot}_{ts}$. The results derived from $\widehat{PGint}_{ts}$ predict a lower baseline expansion on public lands under no drought conditions and a larger increase under dry conditions compared to the results from $\widehat{PGtot}_{ts}$. Considering the intensive pasture expansion variable, the point estimates predict that public land farmers expand their pasture by 3.9% during droughts, compared to 3% in non-drought years. Farmers in private lands expand their pasture, on average, by 3.2% regardless of the dry conditions.

Considering some intensive growth on public lands that we observe as extensive, the jump in public lands growth observed in the "Intensive Pasture Growth" column is underestimated. As the growth under this variable is larger than in "Total Pasture Growth," we must be in the third line of table 1, i.e., both estimators underestimate the pasture growth in public lands. Considering $b^*_{priv} < b^*_{pub}$, both estimators also underestimate the difference in pasture growth between public

Fig. 4: Average Drought Conditions from 2003 to 2022

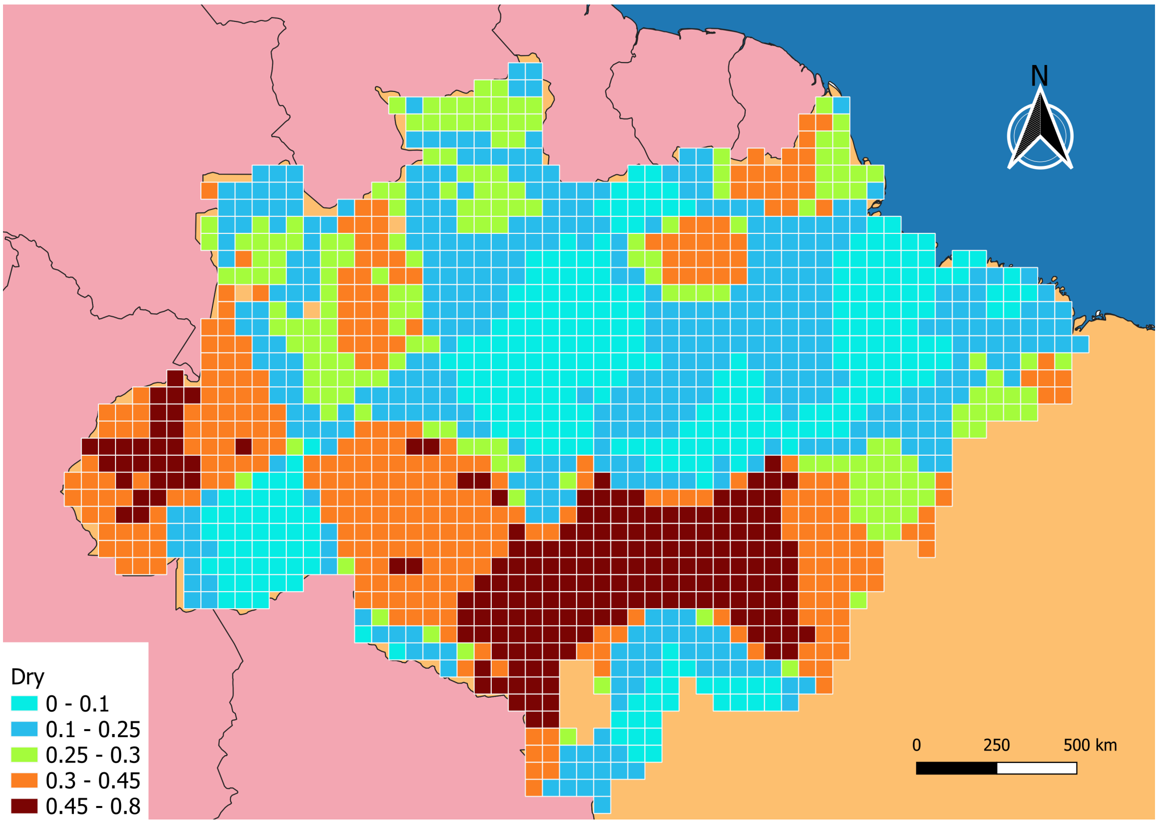
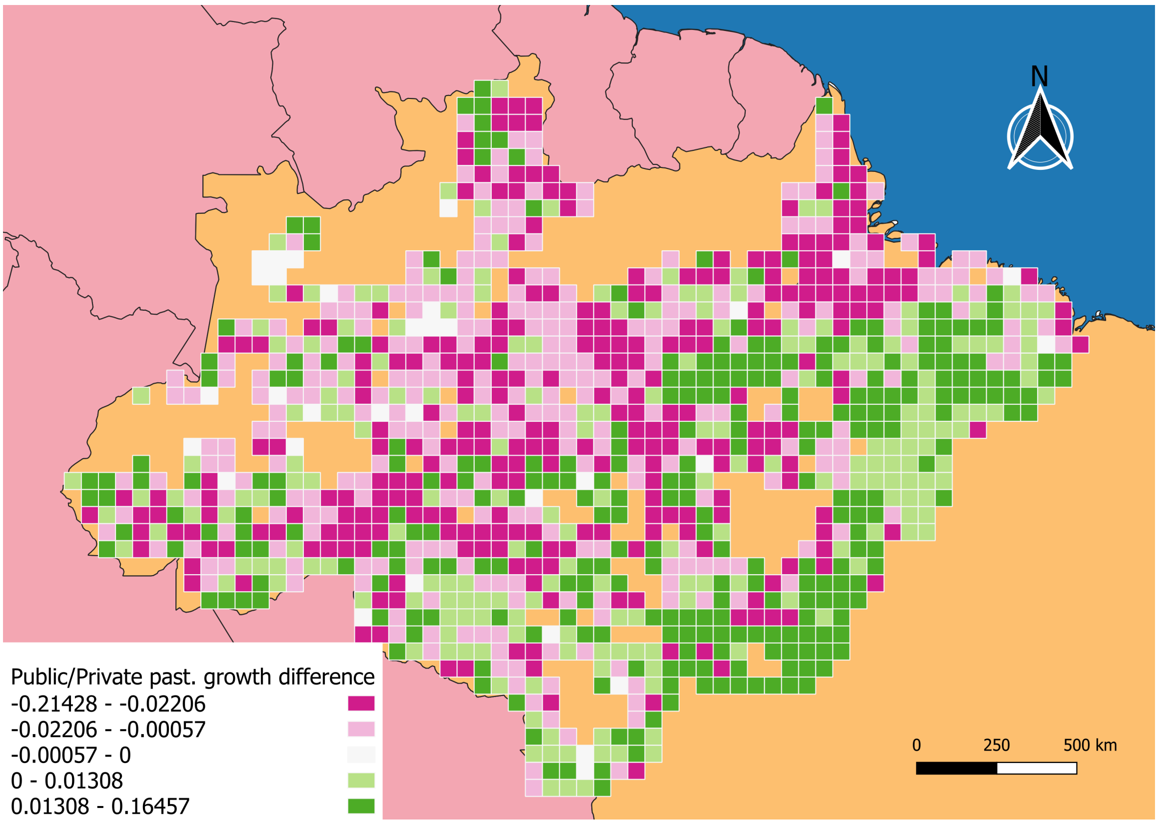
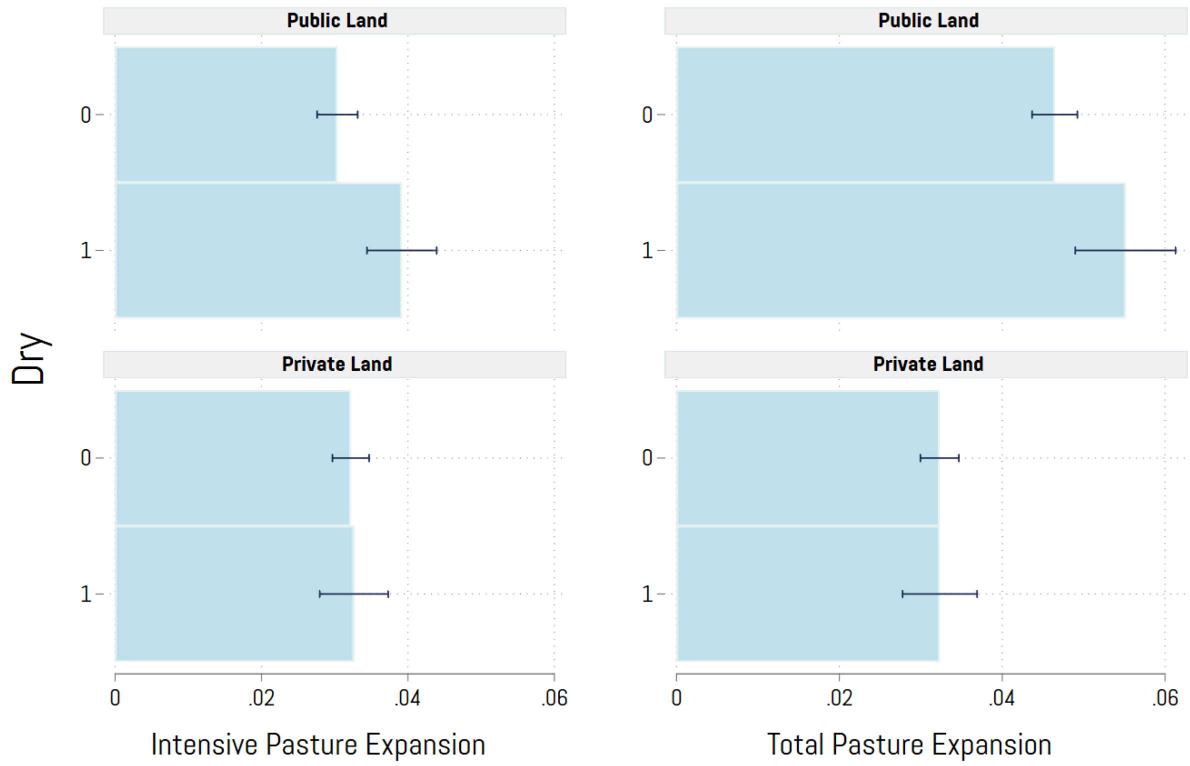


Fig. 5: Average Difference between Public and Private Pasture Growth Rates



Considering only observed intensive growth for public lands

Fig. 6: Droughts and pasture expansion



and private lands.

These results provide evidence that farmers on public lands react more to climate shocks than those on private lands. However, many possible explanations exist for this phenomenon, including fewer incentives to invest and manage the land sustainably, better opportunities to deforest and claim lands during droughts, or different socioeconomic characteristics across public land and private land farmers. We explore some of these mechanisms in the next section.

6.1 Mechanisms

6.1.1 Pasture Degradation

In this section, we explore some possible mechanisms for the observed difference in pasture expansion across public and private land farmers during drought years. First, we investigate the role of pasture degradation between droughts and farmers' land use response. Economic theory postulates that negative productivity shocks, such as droughts, increase the value of outside option activities and thus reduce investment in pastureland. However, in a context of an extensive production system with low capital input and abundant land, drought-induced pasture degradation may lead ranchers to look for new lands.

Furthermore, suppose public land farmers have lower incentives to invest and manage the land sustainably, as expected from the results in section 3. In that case, we should expect that they react more to pasture degradation. We explore these possibilities by first investigating how droughts affect pasture degradation rates and then how the degradation rates affect pasture expansion across each land tenure.

Table 3 shows the impacts of droughts on pasture degradation rate [3]. Droughts increase the pasture degradation rate by 0.5 percentage points, with no different impacts across public and private land pastures. Pasture on private lands, on average, suffers 0.6 percentage points more degradation each year, which could be a result of private farms being older or public land ranchers abandoning the land faster. However, private land pasture could face more visible degradation if those farmers employ a pasture rotation system. In this case, other parts of their pasture area would also regenerate more. The second column of table 3 includes the pasture regeneration rate [4] as a control, and the results do not change significantly.

Next, we investigate how the degradation rate affects pasture expansion across each type of land tenure. Table 4 shows these results. We observe that, for the full and public samples, the effect of droughts on pasture expansion falls once we control for the pasture degradation rate, which is evidence that degradation acts as a mechanism. We also observe that degradation leads to pasture expansion in all samples, which is evidence that ranchers look for new pastureland when their range degrades. Furthermore, this effect is larger for public lands. The results in table 8 in the Appendix, when we interact pasture degradation with land tenure, confirm this difference in responses to pasture degradation. These results are consistent with the hypothesis that farmers in public lands have fewer incentives to invest and manage their farms sustainably.

[3]The Mapbiomas dataset includes data on pasture quality and classifies the pasture into three categories: good, medium, and degraded. We calculate the pasture degradation rate as

$$PDeg_{c,i,t} = \frac{p^{gm}_{c,i,t} + p^{gd}_{c,i,t} + p^{md}_{c,i,t}}{p^{G}_{c,i,t-1} + p^{M}_{c,i,t-1}}$$

where $p^{gm}_{c,i,t}$ is the pasture area classified as good in $t-1$ and medium in t, $p^{gd}_{c,i,t}$ is the pasture area classified as good in $t-1$ and degraded in t, $p^{md}_{c,i,t}$ is the pasture area classified as medium in $t-1$ and degraded in t, $p^{G}_{c,i,t-1}$ is the total pasture area classified as good in $t-1$, and $p^{M}_{c,i,t-1}$ is the total pasture area classified as medium in $t-1$.

[4]Pasture regeneration rate is calculated analogously to the pasture degradation rate. It is calculated as

$$PReg_{c,i,t} = \frac{p^{mg}_{c,i,t} + p^{dg}_{c,i,t} + p^{dm}_{c,i,t}}{p^{M}_{c,i,t-1} + p^{D}_{c,i,t-1}}$$

where $p^{mg}_{c,i,t}$ is the pasture area classified as medium in $t-1$ and good in t, $p^{dg}_{c,i,t}$ is the pasture area classified as degraded in $t-1$ and good in t, $p^{dm}_{c,i,t}$ is the pasture area classified as degraded in $t-1$ and medium in t, $p^{M}_{c,i,t-1}$ is the total pasture area classified as medium in $t-1$, and $p^{D}_{c,i,t-1}$ is the total pasture area classified as degraded in $t-1$.

Tab. 3: Droughts and pasture degradation

	Pasture degradation	
Dry	0.0048***	0.0039***
	(0.0013)	(0.0012)
Private Land	0.0062***	0.0061***
	(0.0011)	(0.0011)
Dry*Private Land	-0.0005	-0.0009
	(0.0014)	(0.0014)
Constant	0.0417***	0.0527***
	(0.0007)	(0.0010)
Observations	26814	26557
R^2	0.4670	0.5062
Regeneration Past. Controls	No	Yes

Standard errors in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Finally, the effect of droughts on public intensive pasture expansion remains significant when we control for degradation, but it disappears when we consider the total pasture expansion. This result is evidence that there are still other mechanisms through which droughts affect intensive public pasture expansion, but other mechanisms likely affect extensive expansion in the opposite direction.

6.1.2 Loosening of environmental regulation

In 2012, the Brazilian Congress enacted a new forest code that, among other measures, grandfathered in irregular properties in public lands established before 2008. A. A. Sant'Anna and Costa 2021 studied the effects of this loosening in environmental regulation and found evidence that this bail-out created incentives for farmers to violate the law in the expectation of receiving future amnesties. At the same time, Brazilian law makes it easier to acquire land tenure if the land is being used productively (Alston, Libecap, and Mueller 1999). Therefore, by making the vegetation more flammable and reducing the cost of deforestation, in the context of post-2012, droughts may create the perfect opportunity for farmers in public lands to expand their productive area and their claim to the land.

We test the hypothesis that there was a break in public farmers' response to drought before and after 2012. Figure 7 shows the results of a regression that allows the impacts of droughts on intensive pasture expansion to differ before and after 2012. We observe that droughts have little to

Tab. 4: Droughts, degradation and pasture expansion

	(1)	(2)	(3)	(4)	(5)	(6)
	Intensive Pasture Expansion					
Dry	0.0046	0.0032	0.0092**	0.0074**	0.0001	-0.0008
	(0.0030)	(0.0029)	(0.0036)	(0.0034)	(0.0030)	(0.0029)
Degrad. rate		0.3158***		0.3159***		0.2656***
		(0.0259)		(0.0376)		(0.0387)
	Total Pasture Expansion					
	(1)	(2)	(3)	(4)	(5)	(6)
Dry	0.0044	0.0031	0.0086*	0.0069	0.0001	-0.0008
	(0.0034)	(0.0033)	(0.0044)	(0.0043)	(0.0030)	(0.0029)
Degrad. rate		0.2707***		0.3050***		0.2656***
		(0.0298)		(0.0418)		(0.0387)
Observations	26814	26814	13389	13389	13395	13395
Sample	Full	Full	Public	Public	Private	Private

Standard errors in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

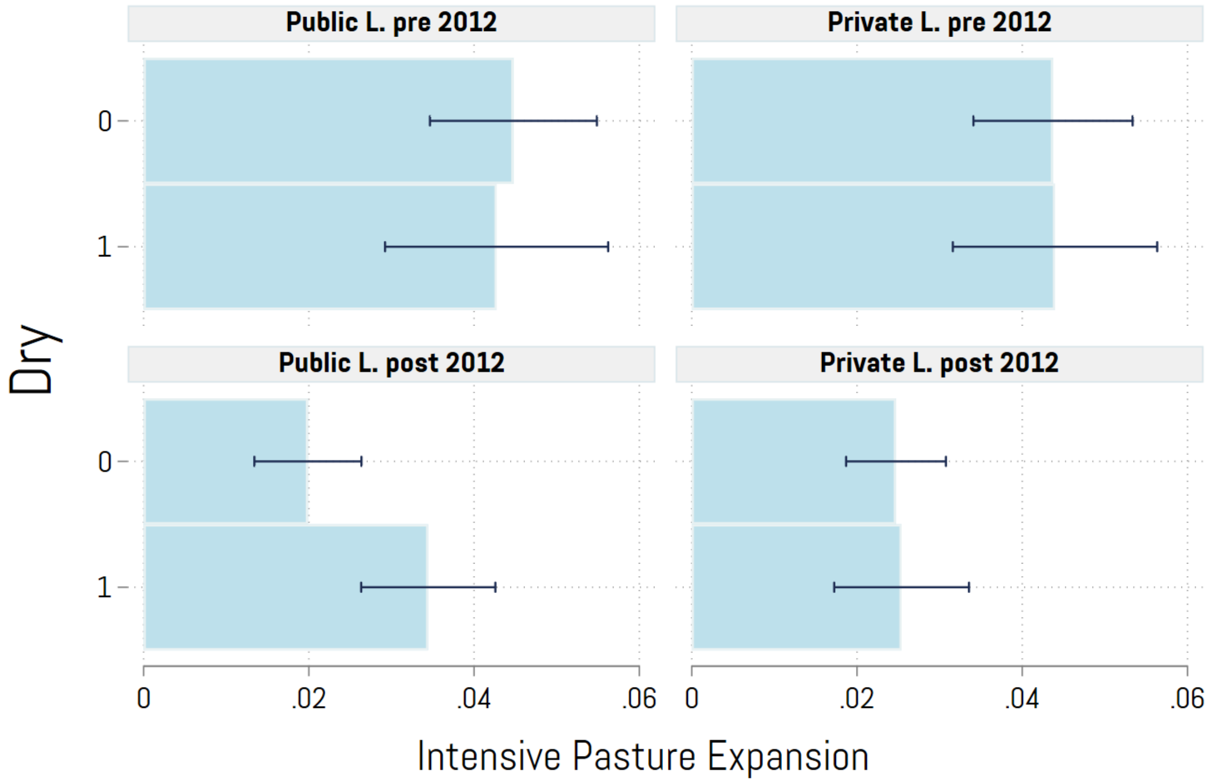
no effect on intensive public pasture expansion in the pre-2012 period, whereas it has a significant impact in the post-2012 period. Droughts seem to have no impact on private expansion in either period. These results are robust when we use total pasture expansion as our independent variable. Figure 16 in the Appendix presents the total pasture expansion results.

These results are consistent with the hypothesis that the loosening of environmental regulation post-2012 created incentives for farmers in public lands to expand their properties, and they take advantage of drier conditions to expand. However, we cannot definitely say that the loosening of environmental policy was the cause of this observed difference in response across the two periods since other important factors differed over the two periods, such as the frequency of drought occurrence. The first period, from 2003 to 2011, was characterized by milder climate conditions. In that period, cells were in drought conditions 17.5% of the time. On the other hand, cells experienced droughts 37% of the time from 2012 to 2022. Therefore, the observed change over the two periods could be due to insufficient statistical power due to the low frequency of droughts.

6.2 Spatial Heterogeneity by Humidity

We also investigate how the effect of droughts on public and private pasture expansion differs by regional humidity. The drought variable we use, based on the SPEI index, considers how the climate conditions within some period of months compare to the historical average climatic conditions of these months for that particular area. This section investigates whether drought impacts in more

Fig. 7: Droughts and intensive pasture expansion pre and post-2012

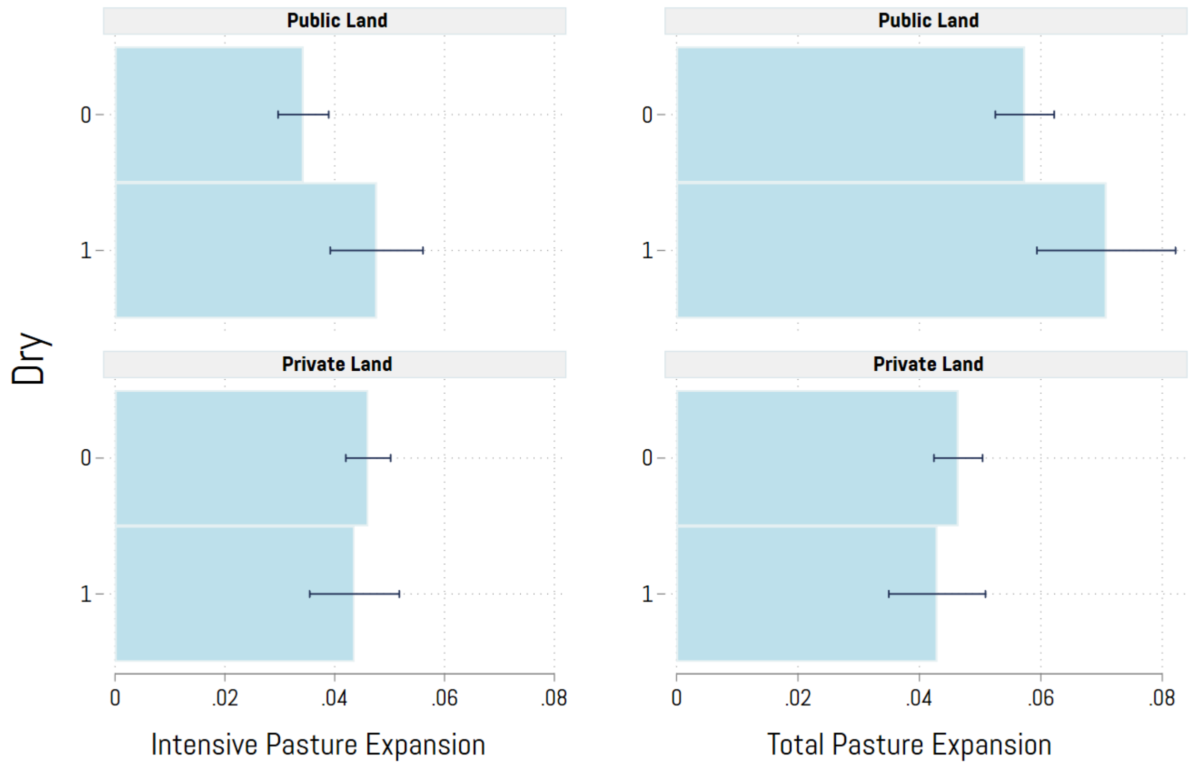


humid regions differ from those in the sample's drier regions. Using the Climate Hazards Group InfraRed Precipitation with Stations (CHIRPS) dataset (Funk et al. 2015), we calculate each cell's average historical rainfall from 1981 to 2000. We then split the sample into below and above-median historical rainfall, where the median for the whole sample from 1981 to 2000 was 2022mm.

Using the same specification as in equation 3, we investigate how the farmers in public and private lands respond to droughts across each subsample. Figure 8 presents the results for the more humid subsample. The results are similar to those presented in figure 6 when we consider the entire sample. Droughts in the more humid subsample lead to increased pasture expansion in public lands for both the intensive and total expansion measures. Like the full sample, private land farmers do not respond to droughts.

The results from the drier subsample in figure 9 depict a different story. Farmers in public lands still expand their pastureland more in dry years, but now farmers in private lands are also responsive to droughts. One possible explanation is that the drier conditions of the area also make private land ranchers less willing to invest in the land, considering an extensive production system with rainfed pasture. Therefore, in drier places, private land ranchers also find it more profitable to look for new ranch areas instead of investing in their land.

Fig. 8: Droughts and pasture expansion in the more humid subsample



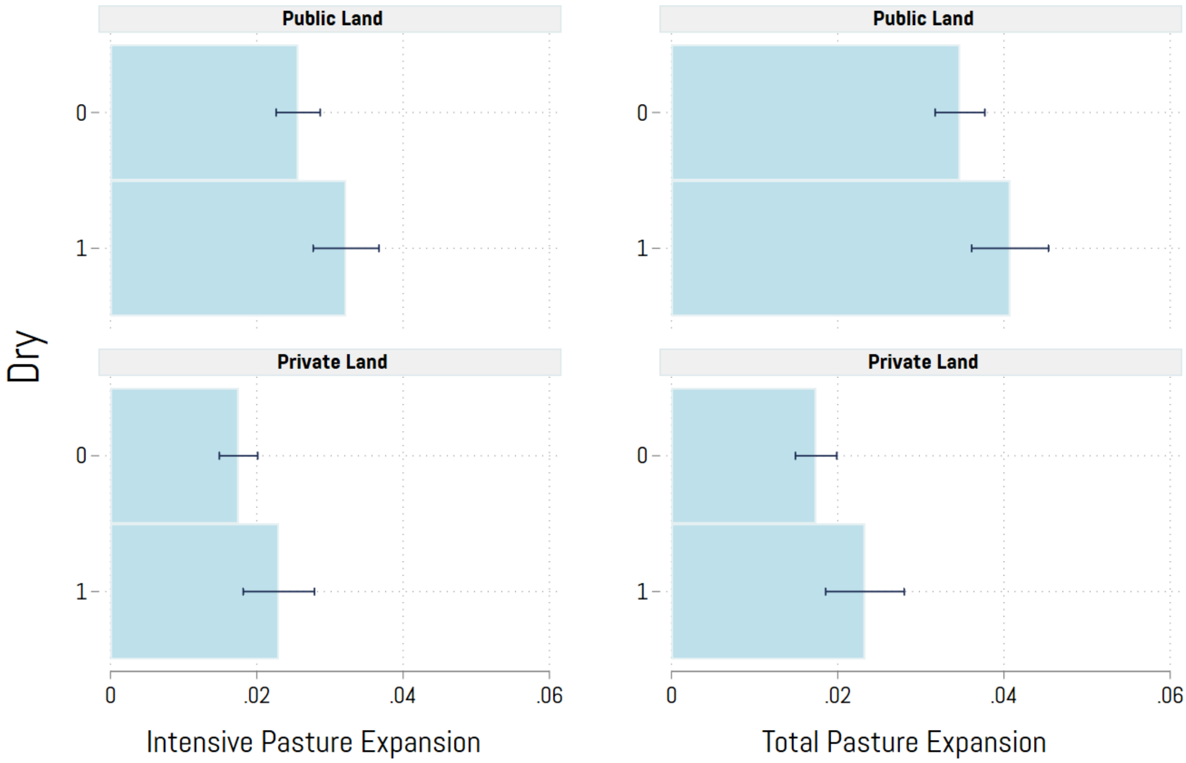
Overall, the results indicate that most observed differences in private and public land ranchers' behavior come from the more humid subsample. While ranchers in public lands always respond to droughts, ranchers in private lands respond only in the drier subsample. This difference in private ranchers' behavior across the subsamples could indicate that higher rainfall levels give ranchers more incentives to invest in the land and restore degraded pastures. However, ranchers in public lands still react to droughts in the humid subsample, as the eviction possibility still discourages any investment in the land.

6.3 Robustness Exercises

6.3.1 Alternative Outcome Variable: Forest to Pasture Conversion

In this section, we test whether our results are robust using another variable as our outcome of interest. Specifically, we use the forest-to-pasture conversion as our alternative outcome variable. The Mapbiomas dataset allows us to observe forested pixels in year $t-1$ converted into pasture in year t. As before, we consider intensive forest-to-pasture conversion if the new pasture area is spatially connected with the pasture area in $t-1$, and total forest-to-pasture conversion accounts

Fig. 9: Droughts and pasture expansion in the drier subsample



for all observed forest-to-pasture conversion.

Table 5 presents the results of estimating equation 3 with our outcome of interest being forest to pasture conversion in square km. The results are similar for both the intensive and total forest-to-pasture conversion variables. Overall, the coefficients have the same sign as our pasture expansion specification but are measured with more noise. This noise could come from measurement errors derived from using remote sensing imagery for land use classification, as described by Alix-Garcia and Millimet 2023.

6.3.2 Alternative Independent Variable: Moderate and Severe Droughts

We also investigate whether our results are sensitive to drought severity. Our main specification defines a drought episode for a given cell c at time t if the SPEI index is below one standard deviation of its historical average for cell c at time t. In this section, we test the robustness of our results to this SPEI index threshold. We define severe and extreme droughts if the SPEI index is below 1.5 and 2 standard deviations, respectively, of its historical average for cell c at time t. Overall, our results are robust to these alternative definitions of droughts. Figures 10 and 11 present the results for

Tab. 5: Droughts and forest to pasture conversion

	Forest to Past. Int.	Forest to Past. Tot.
Dry	0.4996	0.5046
	(0.3272)	(0.3727)
Private Land	3.6069***	3.9726***
	(0.5680)	(0.6567)
Dry*Private Land	-0.6990*	-0.8734*
	(0.4141)	(0.4864)
Constant	5.9229***	6.8437***
	(0.2950)	(0.3390)
Observations	26814	26814
R^2	0.3723	0.3718

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

severe and extreme droughts, respectively. Nonetheless, unlike our main results, figure 11 presents evidence that extreme droughts lead to a slight reduction in pasture expansion in private lands.

6.3.3 Including CAR poor lands

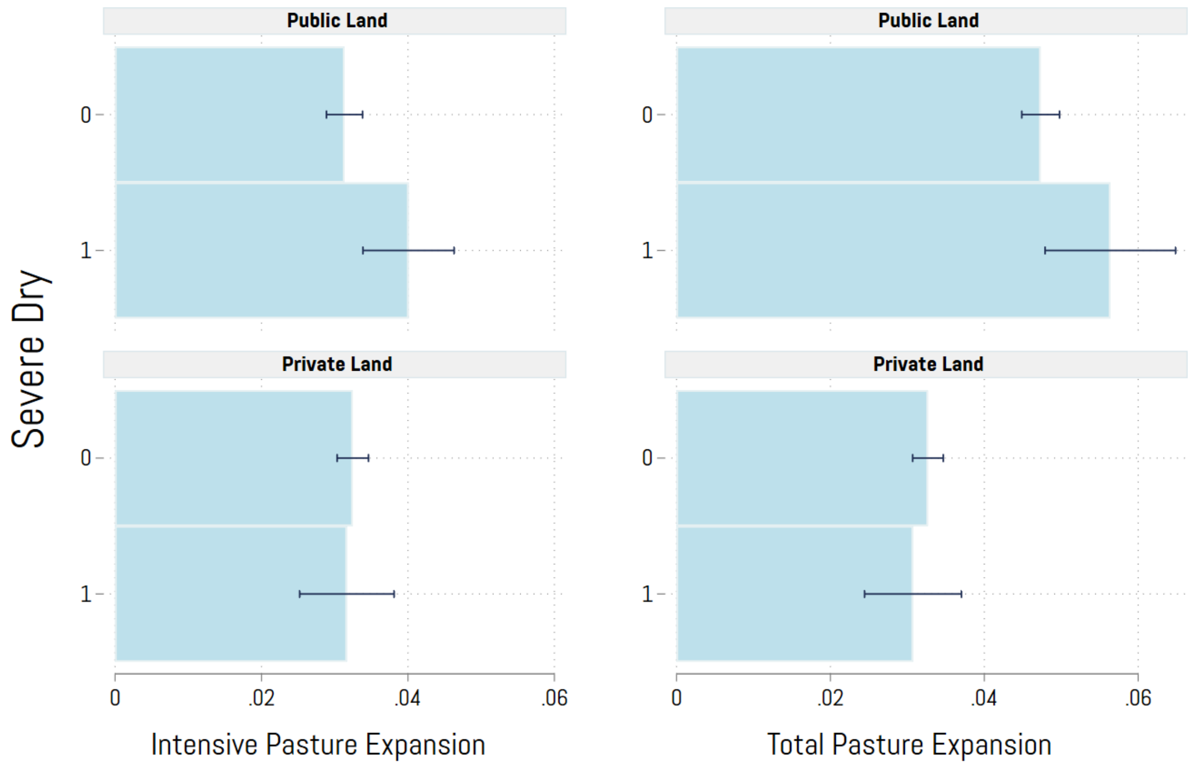
In this section, we reintroduce the CAR poor lands into our data. As described in section 5, CAR poor lands are properties registered in CAR with more than 5% of their area overlapped with other properties. Since these properties are more likely to be invaded public lands, we introduce them in our data in the public lands category. The results, presented in figure 12, are similar to when no CAR poor lands are included.

6.3.4 Fixed Effects

We also investigate whether our results are robust to different fixed effects specifications. Figure 13 shows the results of regressions that include all the combinations of cell and year-fixed effects for intensive pasture expansion. The fixed effects make the *Dry* coefficient more precisely estimated, but the *Dry*Private* interaction coefficient is stable over all combinations of fixed effects. Therefore, even if the basis effect of droughts on pasture expansion depends on the specification, the different response between private and public land farmers is robust in all specifications. These results are similar when considering the total pasture expansion, as shown in figure 17 in the Appendix.

We also investigate if our results are robust to the recent DiD estimators. More specifically, we compare the de Chaisemartin et al. 2022, henceforth CDiD, and two-way fixed effects estimators. Since our baseline model in equation 3 does not include unit fixed effects (which would be tenure-

Fig. 10: Severe Droughts and pasture expansion

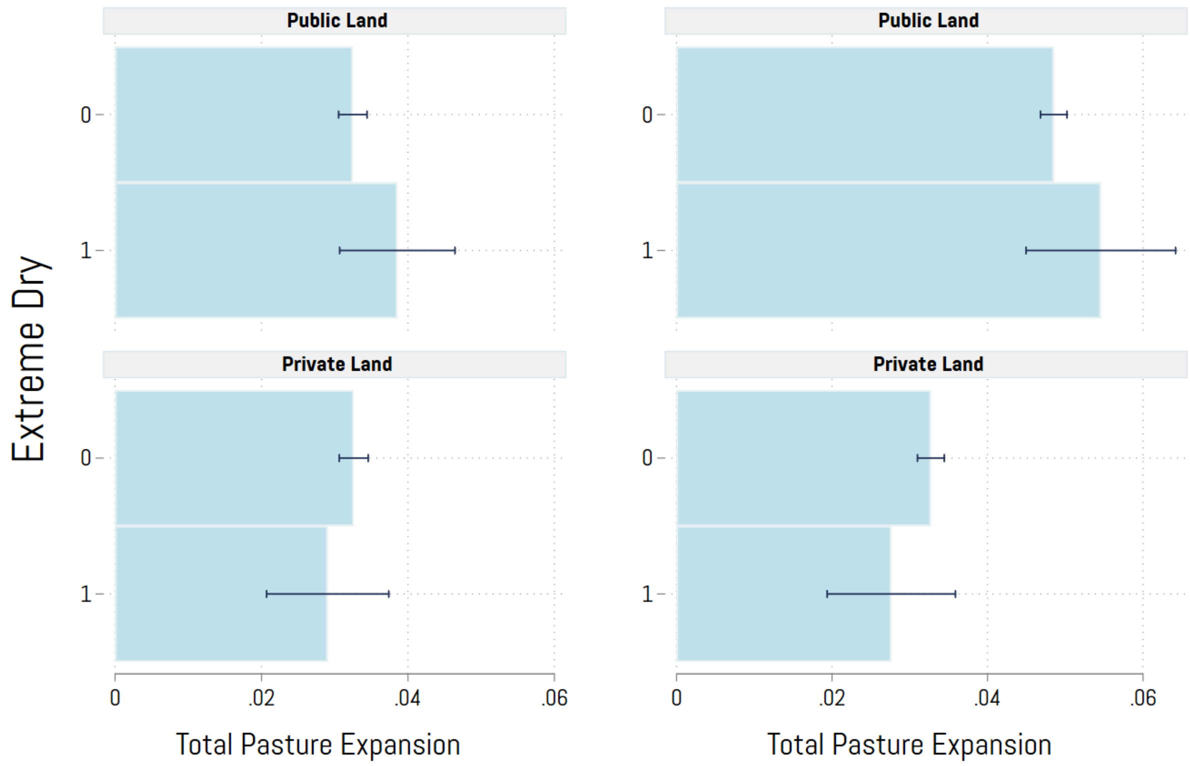


by-cell fixed effects) and the recent DiD estimators, such as CDiD, always include unit fixed effects, we compare the CDiD estimator to the following two-way fixed effects model:

$$y_{cit} = \beta_0 + \beta_1 Dry_{ct} + \gamma_{ci} + \delta_t + \varepsilon_{cit} \tag{4}$$

where γ_{ci} is the unit (tenure-by-cell) fixed effect. We estimate the equation 4 and CDiD models for each private and public subsample. The results are shown in table 6. Compared to the CDiD, the TWFE estimator underestimates the impacts of droughts on both private and public lands. However, the CDiD estimator still predicts a larger impact of droughts on public lands compared to private lands. The CDiD estimator predicts that droughts lead to a pasture expansion of 1.31% or 1.11% for the intensive and total expansion metrics used, respectively. The same estimator predicts an expansion of 0.32% of pasture on private lands. It is worth noting, however, that compared to the CDiD, the TWFE estimator greatly underestimates the impacts of droughts on private lands (0.01% vs. 0.32%). Nonetheless, for both estimators, droughts' impact on private lands is not statistically different than zero at the 5% significance level. On the other hand, both estimators predict a positive and statistically significant impact of droughts on public lands pasture expansion, regardless of the metrics used.

Fig. 11: Extreme Droughts and pasture expansion



6.3.5 Sample Trimming

We also investigate whether our results are driven by the specific thresholds in pasture and forest cover we use for trimming. In our original specification, we trim our sample to include cells in which both public and private lands have at least 1 km^2 of pasture in the previous year and at least 10% of forest cover in 2001. We find that changing the pasture thresholds to 3 km^2 and 5 km^2, and the forest cover in 2001 to 15% and 20% do not change our results. Figure **??** shows the results for intensive pasture expansion. The results for total expansion, which are similar, are presented in figure 18 in the Appendix.

6.3.6 Conley Spatial Standard Errors and Weights

Considering that cells have different compositions of pasture and forests within their public and private lands, we want to compare how pasture growth responds to dry conditions in cells with a similar composition of pasture and forest across different land tenures. Here, we test whether giving greater weight to cells with similar public and private land cover compositions changes our results. Let $p_{pub} = \frac{pasture}{pasture+forest}$ in public lands, and $p_{priv} = \frac{pasture}{pasture+forest}$ in private lands. Our weights take the form $1 - |p_{pub} - p_{priv}|$, thus giving more weight to more balanced cells. Figure 15 shows

Fig. 12: Droughts and pasture expansion including CAR poor lands

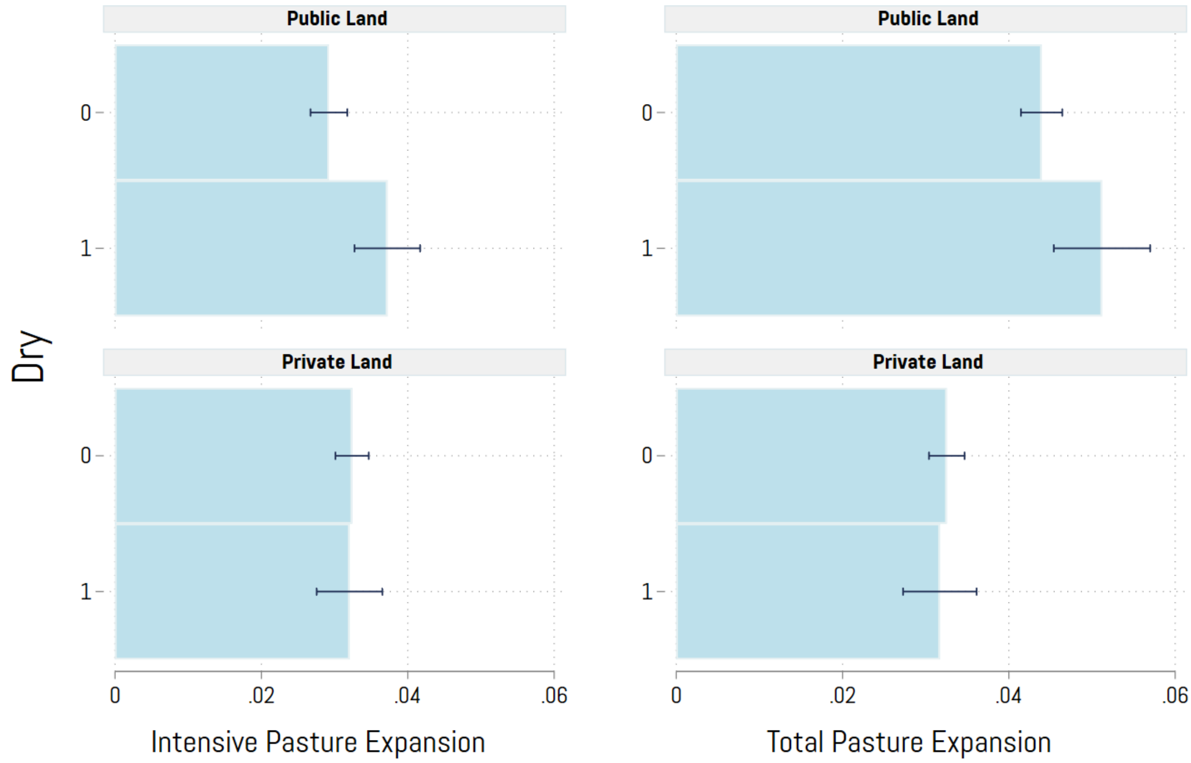
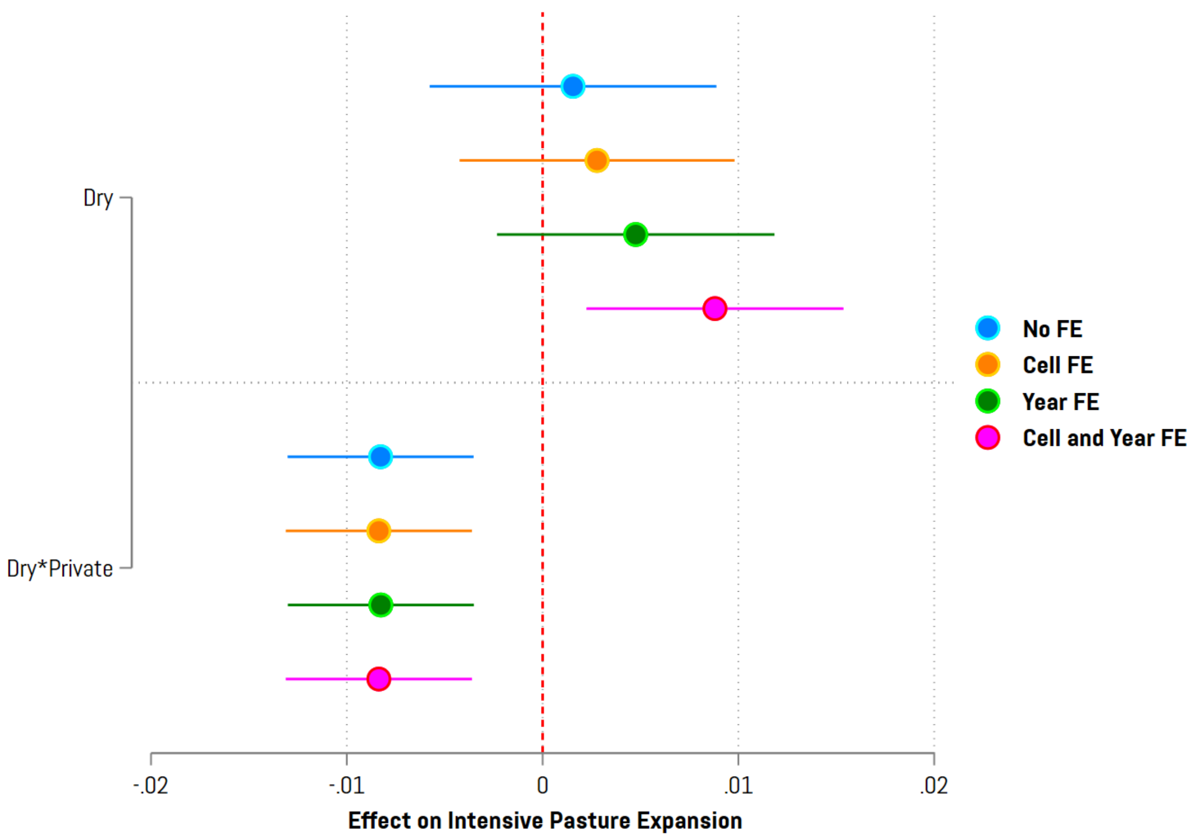


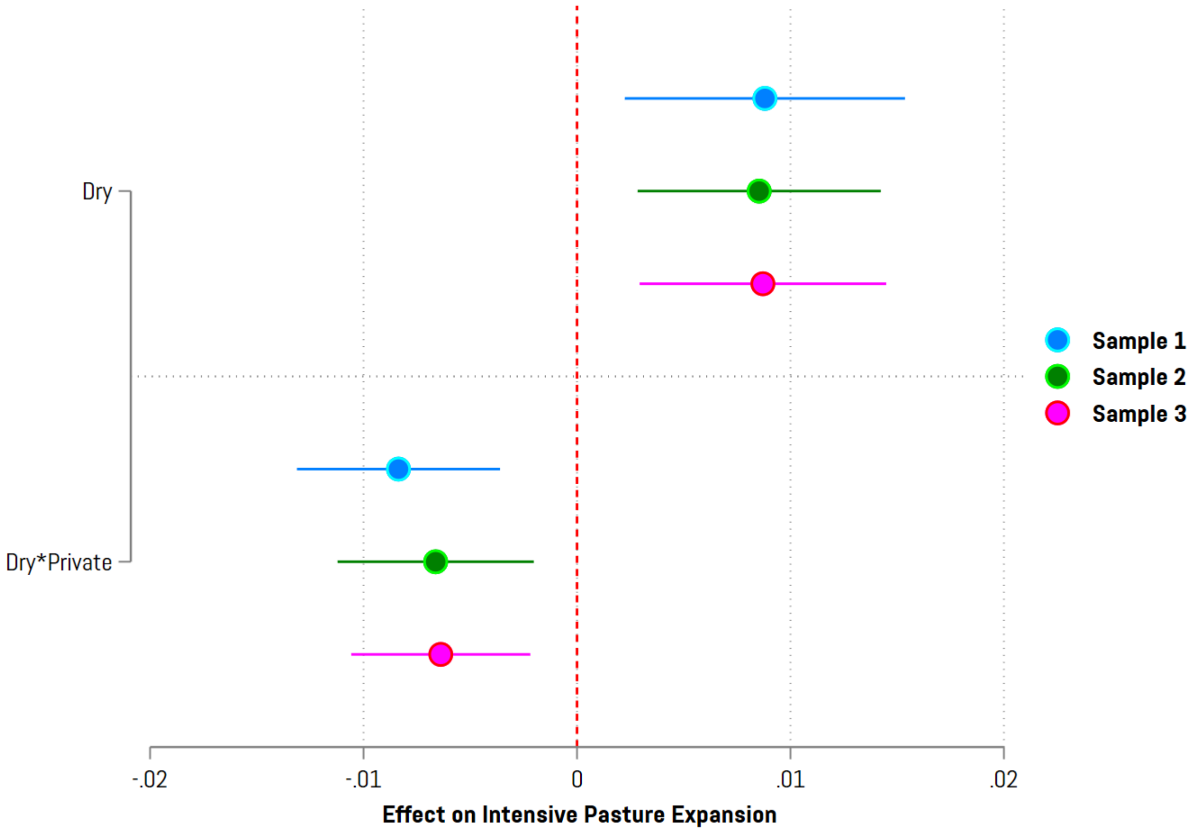
Fig. 13: Different fixed effects specifications, intensive expansion



Tab. 6: TWFE and de Chaisemartin et al. 2022 estimates

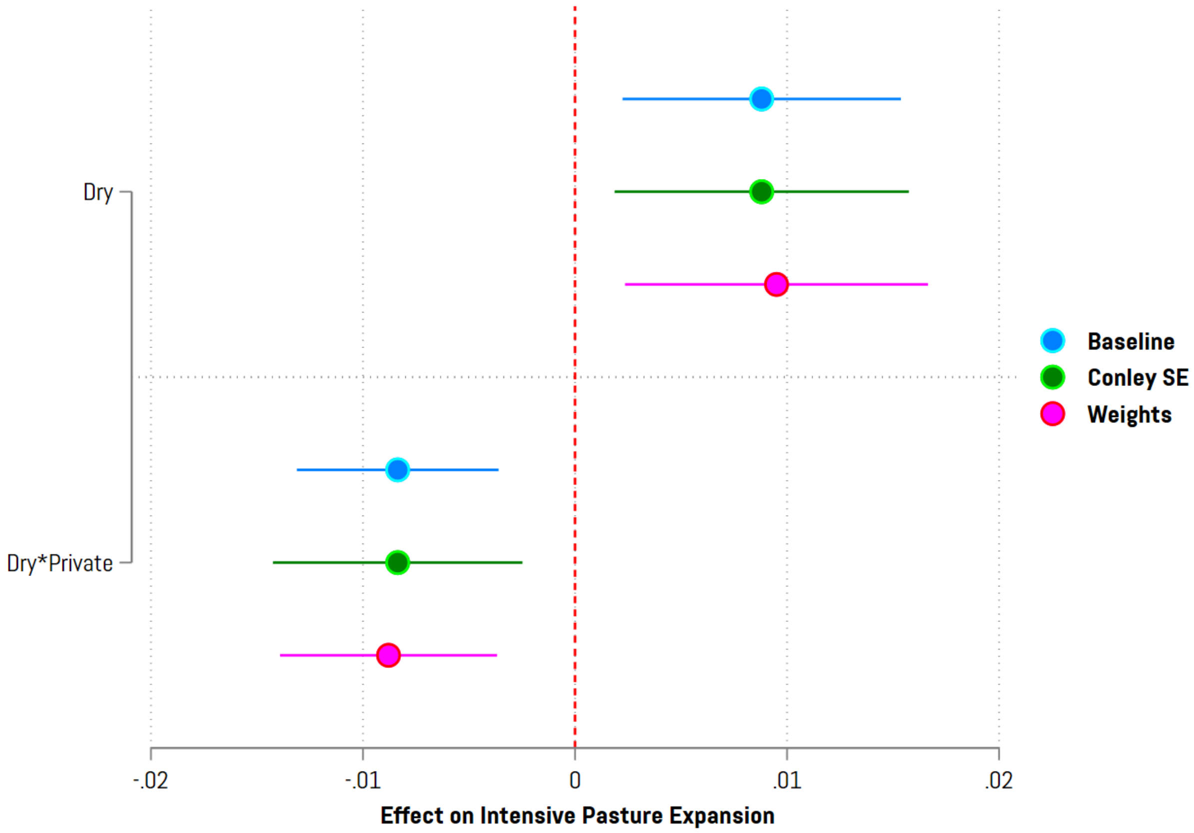
		Estimate	SE	LB CI	UB CI
Intensive Pasture Expansion					
Public	TWFE	0.0092	0.0036	0.0021	0.0162
	CDiD	0.0131	0.0042	0.0050	0.0213
Private	TWFE	0.0001	0.0030	-0.0059	0.0061
	CDiD	0.0032	0.0024	-0.0014	0.0078
Total Pasture Expansion					
		Estimate	SE	LB CI	UB CI
Public	TWFE	0.0086	0.0044	0.0000	0.0173
	CDiD	0.0111	0.0051	0.0010	0.0211
Private	TWFE	0.0001	0.0030	-0.0059	0.0061
	CDiD	0.0032	0.0030	-0.0026	0.0090

Fig. 14: Different trimming samples, intensive expansion



S1 corresponds to a sample in which both public and private lands within a cell have at least 1 km^2 of pasture in the previous year and at least 10% of forest cover in 2001. S2 corresponds to a sample with thresholds of 3 km^2 of pasture and 15% of forest cover in 2001. S3 corresponds to a sample with thresholds of 5 km^2 of pasture and 20% of forest cover in 2001.

Fig. 15: Conley SE and weights, intensive expansion



that these weights do not change our results significantly. Figure 15 also shows that using Conley standard errors with a 200 km threshold does not impact our standard errors significantly. Figure 15 in the Appendix shows the same exercise for total expansion, with similar results.

7 Concluding Remarks

This paper investigates how farmers in different types of land tenure respond to climate shocks. Ranchers in public lands expand their pastureland more during drought years when compared to private land ranchers. This result is consistent with the economic premise that positive eviction rates cause ranchers to discount the future more, and therefore, public land ranchers are less willing to invest in the land and restore degraded pastures. By expanding their pastureland during droughts, farmers in public lands are able to mitigate the negative climate effect by bringing forestland into use. On the other hand, private land farmers have more incentives to restore degraded pastures and make their land more productive in the long term, especially in humid areas. Investigating the possible mechanisms behind these results, we find that farmers in public lands respond more to pasture degradation, which is consistent with the theory above.

We also find that the effects of droughts in public land pasture expansion remain positive and statistically significant even after controlling for pasture degradation, which is evidence that other mechanisms are at play. We investigate whether the environmental code modifications of 2012 gave farmers in public lands incentives to claim more land by expanding their productive area. We find that our results are driven by the post-2012 period. These findings are consistent with farmers in public lands using droughts as an opportunity to deforest and claim land after the environmental deregulation after 2012 and could help explain why the effect of droughts on public pasture expansion remains positive and statistically significant after controlling for pasture degradation. Nevertheless, we cannot undoubtedly attribute these post-2012 results to environmental deregulation since there are other important differences between these two periods. For instance, the pre-2012 period was characterized by milder climate conditions, whereas droughts were more frequent in the post-2012 period.

However, we must interpret these results with caution. We observe more pasture expansion in public lands during drought years, but our data does not allow us to conclude that these observed discrepancies are caused by land tenure. Farmers in public and private lands are inherently different from each other in socioeconomic terms. For instance, our results could be driven by different mitigation strategies by farmers of distinct income groups if farmers in public lands are poorer on average than those in private lands. Furthermore, our work focuses on droughts' short-term impacts across the different land tenure classes. Our results cannot tell us what the differences in deforestation across land tenure would be if the whole region became drier in the long term.

Our work presents new opportunities for future research. First, there is a need to better understand the differences between farmers in public and private lands at the farm level and how socioeconomic disparities could drive different responses to droughts. Second, future work should investigate the long-term effects of droughts on land-use decisions. A drier climate should induce land use conversion to drought-tolerant agricultural activities. However, differences in land tenure could induce diverse incentives for this long-term adaptation to a drier climate.

Overall, these results provide evidence that the increased occurrence of droughts under climate change expands the pressure on public land forests. Land use change driven by even short-term climate deviations can contribute to the erosion of the local environment. Since public lands cover more than two-thirds of the Amazon, the public forests represent a gigantic carbon stock, and their vulnerability makes it challenging to curb climate change. Our results should guide policymakers to increase the monitoring of public lands during drought years, design mechanisms to better enforce public property rights, and impose a tax on extensive cattle ranching. However, they do not provide information that either land tenure would perform better in environmental measures under permanent drier conditions.

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Appendices

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Tab. 7: Droughts and pasture expansion

	Intensive Past.	Total Past.
Dry	0.0088***	0.0087**
	(0.0033)	(0.0042)
Private Land	0.0018	-0.0141***
	(0.0021)	(0.0017)
Dry*Private Land	-0.0084***	-0.0087***
	(0.0024)	(0.0030)
Constant	0.0304***	0.0464***
	(0.0014)	(0.0014)
Observations	26814	26814
R^2	0.2242	0.2296

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Tab. 8: Droughts and pasture degradation

	Intensive Past.	Total Past.
Degrad. rate	0.3942***	0.3420***
	(0.0309)	(0.0342)
Private Land	0.0049**	-0.0134***
	(0.0023)	(0.0022)
Degrad. rate*Priv. Land	-0.1605***	-0.1089***
	(0.0387)	(0.0392)
Constant	0.0160***	0.0342***
	(0.0016)	(0.0016)
Observations	26814	26814
R^2	0.2375	0.2380

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Fig. 16: Droughts and total pasture expansion pre and post-2012

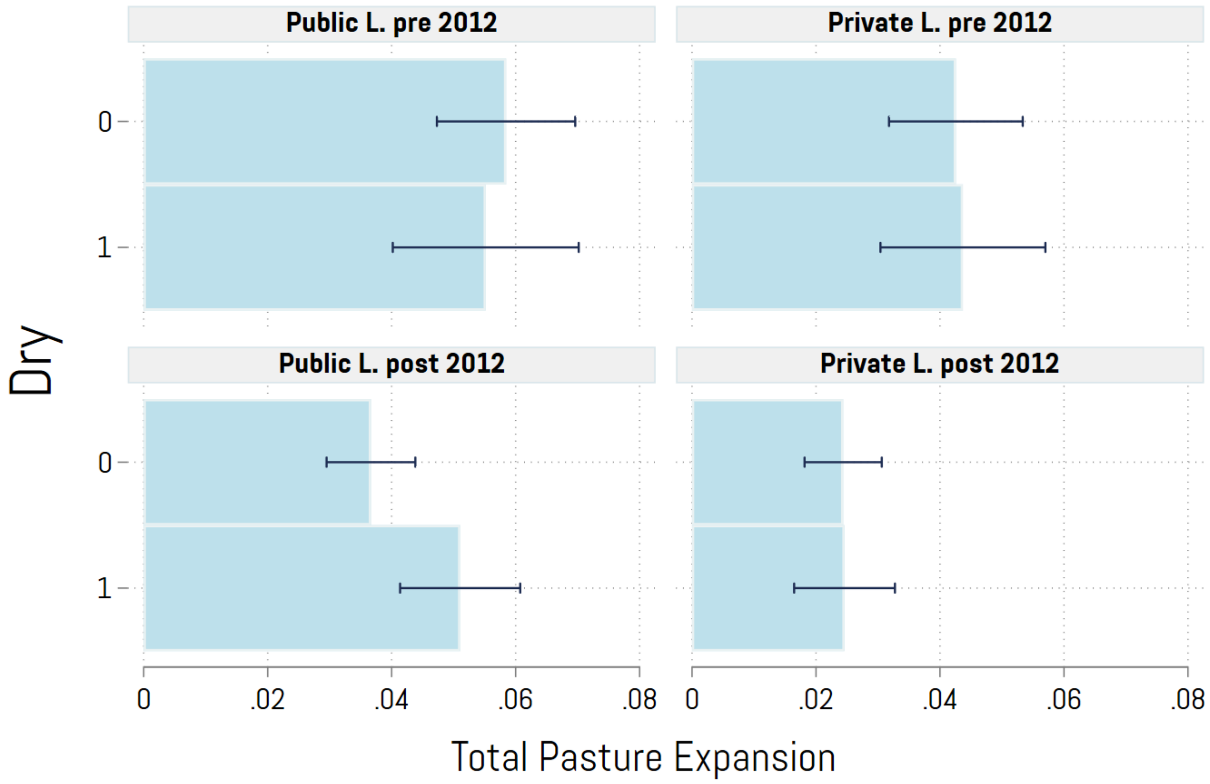


Fig. 17: Different fixed effects specifications, total pasture expansion

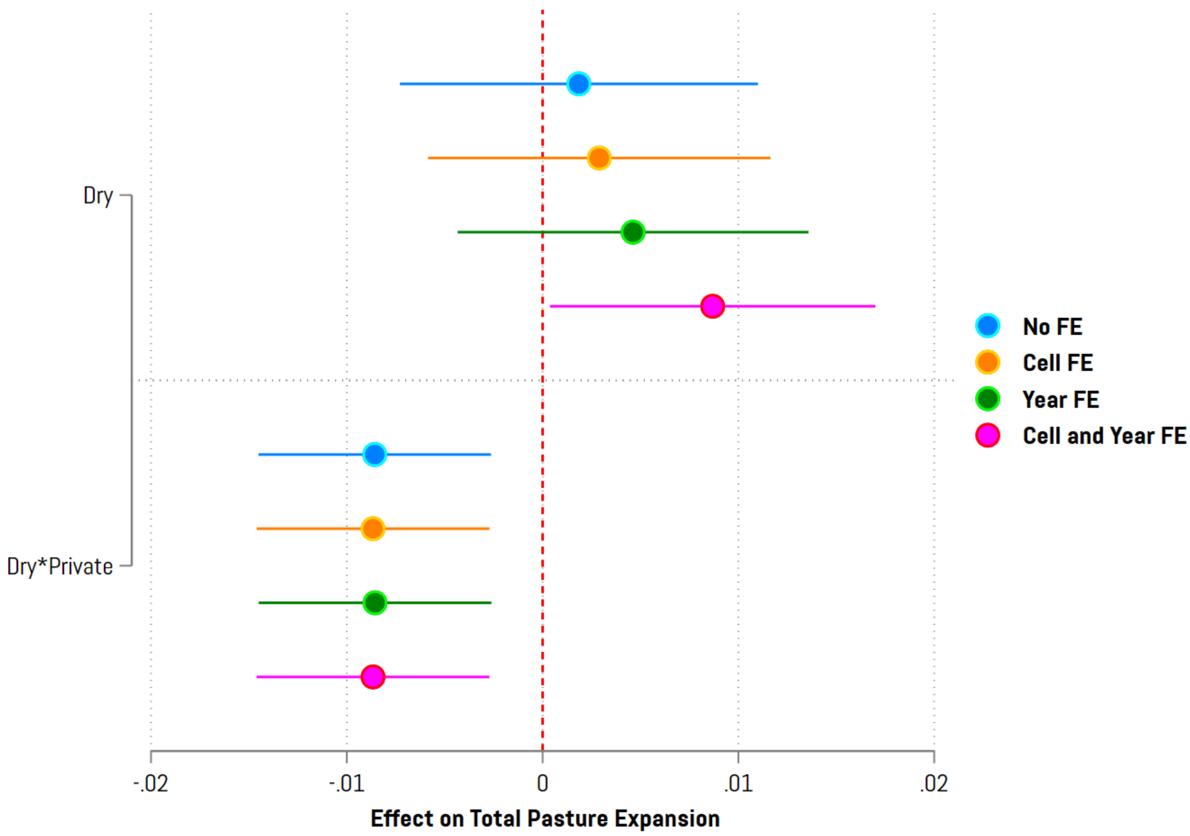
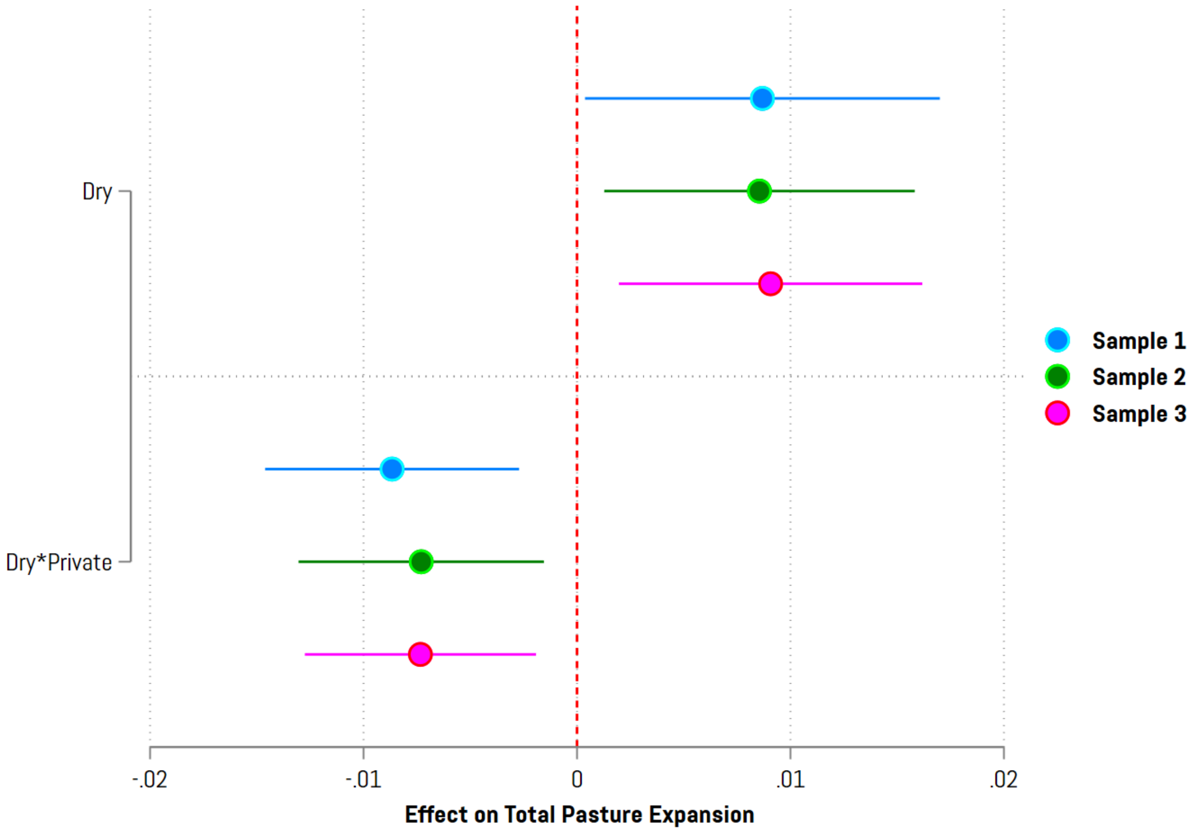


Fig. 18: Different trimming samples, total expansion



S1 corresponds to a sample in which both public and private lands within a cell have at least 1 km^2 of pasture in the previous year and at least 10% of forest cover in 2001. S2 corresponds to a sample with thresholds of 3 km^2 of pasture and 15% of forest cover in 2001. S3 corresponds to a sample with thresholds of 5 km^2 of pasture and 20% of forest cover in 2001.

Fig. 19: Conley SE and weights, total expansion