Title

Large-scale green grabbing for wind and solar PV development in Brazil

Authors

Klingler, Michael[1]; Ameli, Nadia[2]; Rickman, Jamie[2]; Schmidt, Johannes[1]

[1] Institute of Sustainable Economic Development, University of Natural Resources and Life Sciences Vienna, AT

[2] Institute for Sustainable Resources, University College London, UK

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Short abstract

Large-scale wind and solar photovoltaic (PV) infrastructures are expanding rapidly in Brazil. These projects can exacerbate struggles for land rooted in weak land governance, with negative impacts for traditional populations due to loss of access to common lands. Here, we trace how green grabbing, i.e. the large-scale appropriation and control of (undesignated) public lands, both formally legal and illicit, for low-carbon technologies, has developed in Brazil throughout 2000 to 2021. We find that global investors and owners, mainly from Europe, are involved in 78% of wind and 96% of solar PV parks, occupying 2,148 km^2 and 102 km^2 of land, respectively. We also show that land privatization is the prevalent land tenure regime for securing access to and control over land, indicating significant transformations of prior(undesignated) public land. We conclude that green grabbing is a persistent, critical phenomenon in Brazil, requiring transparency and close monitoring of land tenure modifications.

Keywords

Green grabbing; large-scale land appropriation; wind power; solar PV; Brazil

Main

Brazil has witnessed a rapid growth of wind power and solar photovoltaic (PV) installations, known as variable renewable energies (VRES), since 2010. During the period from 2011 to 2021[1], the installed capacity of wind power increased from 1.2% to 11.4%, while solar PV capacity rose from 0.1% to 2.6%. Future energy plans, including the Ten-Year Energy Expansion Plans (2029/2031) and the long-term National Energy Plan 2050, project significant further growth in wind and solar PV energy. By 2030, wind power is expected to double, and by 2050, it is anticipated to increase eleven-fold compared to 2021. Similarly, solar PV is projected to double by 2030 and increase forty-fold by 2050[1]. The expansion is driven by the demand for higher electricity generation due to demographic and economic factors. It is also a crucial aspect of Brazil's energy and climate policies, aimed at reducing reliance on hydropower especially during drought season, and diversifying energy sources[2,3]. However, studies point to the risk that continuities of resource-based territorial conflicts are reproduced by illegal land acquisition and insecure tenure, causing negative impacts for traditional rural communities and indigenous peoples[4,5]. The expansion of VRES is no exception here: VRES projects, particularly in the Global South, are often linked to land struggles rooted in unequal patterns of land ownership, non-recognition and loss of access to common lands and communal land use rights[6–8].

The phenomenon of large-scale land and resource acquisition gained notoriety as land grabbing, global land rush, or new enclosures following the financial crisis and food prices spike in 2007-08[9–11]. In earlier stages research on land grabbing was primarily linked to transnational deals and large-scale investments in farmland for food and fuel crops[12–14]. However, the notion of green grabbing[15] emerged, emphasizing how securing access to and control over land is enabled by carbon sequestration technologies[16], biodiversity conservation[17], or renewable energy production[18–20]. The definitions of land grabbing and green grabbing are controversial and subject to political contestation[21]. They encompass various aspects such as the scale of land deals, their impact on local communities, and the involvement of foreign actors and capital. A key element addresses "control grabbing"[22] of relatively vast tracts of land and natural resources through diverse mechanisms and forms, often driven by large-scale capital responding to the convergence of food, energy and financial crises and demands for resources, and increasingly conditioned by climate change mitigation imperatives.

In the Brazilian context, land grabbing research has mainly focused on illegal deforestation in the Amazon[23–25], but the nexus between VRES expansion, investment flows, and land tenure which characterizes green grabbing, remains poorly understood. Global databases, such as the Land Matrix aim to monitor large-scale land transactions to promote transparency and accountability[26]. However, due to the sparse availability of investment and land tenure data, the empirical assessment of the impacts of green grabbing by VRES is contested, especially in terms of quantitative and spatially explicit analysis. Land tenure in Brazil is marked by high insecurity, with territorial disputes, social conflicts and violence, due to historical inequalities in land ownership, lack of land regulation, and weak governance[4,5,27]. There exist a variety of claims to the use and control of private, public, or undesignated public lands made by large landholders, smallholders, the landless, as well as traditional communities and Indigenous peoples. Additionally, the capital-intensive nature of VRES expansion involves large-scale investments from international and national government or corporate entities[28]. This complex setting, coupled with incomplete or outdated land ownership records and overlapping land-tenure designations, present challenges when tracking and documenting land deals related to VRES projects.

By combining several datasets from a wide range of sources, we are able to trace the evolution of green grabbing in Brazil from 2000 to 2021 in the context of the expansion of VRES. Our study provides a detailed assessment, both quantitatively and spatially, of the scale of green grabbing for wind and solar PV park areas. It analyzes the intricate relationships among international and domestic actors involved in the development and financing of these parks. Furthermore, we assess the land tenure situation of the parks to shed light on various control grabbing dynamics. To achieve this, we integrate publicly available geo-referenced data from the Brazilian Electricity Regulatory Agency (ANEEL), the National Property Certification System (SNCI) and the Land Management System (SIGEF), the Rural Environmental Registry System (SICAR) with global investment and ownership data from Bloomberg New Energy Finance (BNEF).

Our results characterize green grabbing by relating large-scale capital investment to the acquisition of land control through land tenure modification. First, we show European actors, such as the Italian Enel SpA and Actis LLP from the UK, are driving large-scale appropriation and control of land for wind and solar PV parks, acting as direct owners. While both national and international players influence financing and ownership in wind parks , 90% of owners and 74% of investors of solar PV assets come from abroad, and mainly from Europe. Second, our analysis reveals that 94% of solar PV park areas have been privatized, while this share is lower for wind parks at 64%. Particularly wind parks are also affected by illicit land claims, e.g., by the use of environmental regulation titles (CAR), which are controversial in Brazil as a means to legitimize land grabbing but do not provide definitive land ownership.

Green grabbing by large-scale investments and land appropriations for VRES

Green grabbing is characterized, from a political economy perspective, by the large-scale appropriation and market-based abstraction, commodification, and marketization of land and resources. This process creates new relations of land control[29] that involve specific types of concession regimes, modifying and transferring ownership, possession, and use rights over public and private land. The phenomenon of green grabbing is closely linked to land grabbing, but it is particularly distinctive by setting green agendas as justification for the appropriation of nature[15]. In this context, various arrangements for securing and controlling land and resources emerge, ranging from direct and forced to politically-institutionally regulated or market-based approaches, and often leading to legally and socially accepted variants of land expropriation and dispossession[30,31]. Land acquisitions and deals associated with the implementation of low-carbon technologies and infrastructure, such as wind power and solar PV, show intricate and often subtle interconnections with climate change politics and sustainable development approaches that, in principle, increase the political legitimacy of land tenure transformations, or even contribute to the amnesty of prior illegal land grabs[21]. Whereas these deals do not necessarily entail a wholesale transfer of land in sales and dispossession from existing claimants, they do lead to a comprehensive restructuring of legal rules and authority over land and resource access, use and management, potentially causing significant alienating effects[21,29].

In the case of Brazil, several attempts have been initiated to organize land appropriation by private and public interests, but there is still a lack of a comprehensive national territorial management system that integrates key land institutions and land databases for regulating public and private land claims at various scales. The institutional framework for land regularization involves multiple widely ramified entities, including Federal and State governments as well as local notary systems, often prone to inconsistencies and uncertainties in land possession and ownership[4,27]. Rural areas, in particular, face systemic challenges in land tenure management, with overlapping land claims from different interest groups – affecting 50% of the registered territory in Brazil[5]. Legislative revisions by the Federal and State governments further contribute to an environment conducive to land speculation and illicit appropriation with widespread risk of volatility in the land market. The increasing digitization, particularly through georeferenced determination of land tenure using digital cadastres and land registries, has contributed to further data conflicts caused, e.g. from overlapping land claims due to illicitly forged land titles or mapping errors[5,32]. Land tenure insecurity and conflicts are particularly prevalent on undesignated (or untitled) public lands (known as *terras devolutas*), which historically have been occupied and collectively used in part by traditional communities as common lands[33–35]. However, these areas are also frequently identified in energy provision forecasts and mapping initiatives with large geophysical potential for large-scale deployment of wind power and solar PV[36,37].

Investment and ownership relations

Based on these initial considerations, we conceptualize green grabbing as the large-scale appropriation of land and tenure control, both formally legal and illicit, for the expansion of wind and solar PV projects involving large-scale national or international capital. To understand the characteristics of actors involved in such projects, we rely on the global investment and ownership BNEF database on wind and solar assets. It reports information on project owners and investors associated with each asset, providing detailed insights into the actors involved directly in green grabbing. 'Direct owners', who are typically renewable energy companies responsible for owning and operating a specific asset. They oversee the entire project lifecycle, starting from an initial feasibility study, and progressing through planning permissions, site design and preparation and finally installation and commissioning. The direct owners or project developers can also be subsidiary companies affiliated with 'parent owners'. International parent owners may choose to develop and operate an asset through a regional branch to more effectively access local services and supply chains and leverage the knowledge and expertise of local personnel. For example, the Spanish energy company Iberdrola operates in Brazil through its subsidiary Neoenergia. More generally, parent owners often operate under limited liability, which protects them from financial losses incurred by their subsidiaries. While parent owners hold the controlling interest (greater than 50%) in the asset, additional investment is often sought by selling equity or raising debt through corporate bonds or loans. Equity and debt investors, holding a non-controlling interest in the asset, are typically not involved directly in project development but will conduct their own risk assessment of the project's viability prior to a final investment decision. These 'strategic investors' may enter the project at different stages of its life cycle, depending on their risk-appetite. These 'direct investors' may themselves be subsidiary companies of larger 'parent investors' that operate through regional branches. For example, an international bank such as the Arab Banking Corp BSC may extend a loan to a Brazilian renewable energy company through its subsidiary Banco ABC Brasil SA. In this way, international investors with expertise and experience in renewable energy financing can better access new and emerging markets such as Brazil[38].

Modes of land appropriation

In addition to identifying international and domestic actors involved in financing and owning assets, we also assess different modes of land appropriation for the development of wind and solar PV parks. Land tenure insecurity is a key issue in Brazil's low-carbon energy transition, as competing claims and poorly defined as well as enforced tenure rights characterize the situation, particularly on public and undesignated public lands. To understand the specific land tenure designation in park areas, we rely here on publicly available national data sets. The National Institute for Colonization and Agrarian Reform (INCRA) provides the most comprehensive information on formal land tenure, including private and public land. We cluster the following core tenure regimes for this analysis: (1) Private land, (2) Public land, (3) Undesignated public land (Supplementary Table 1 for details on the digital land tenure system). Private land is further distinguished between 'licit' private property titles, and private claims in the form of rural environmental registries, known as CAR titles. The former are issued by INCRA and registered in the Federal digital land tenure systems SNCI-SIGEF[39], and may involve privatization of previously public or undesignated public land. In contrast, the CAR provides self-declared environmental information from rural private properties and land claims related to land use and land cover[40]. The Brazilian Forest Code (Law 12,651/2012) requires landowners to submit CAR titles, including property boundaries and land use types, to the public electronic registry SICAR, however, the subsequent validation process by state environmental agencies has been exceptionally slow to date (2% of 618.8 million ha property area validated by 2022[41]). This situation increases the potential for fraud, which is why the CAR has been criticized also as a tool for land grabbing, especially since the legislative change by MP857 (now Law 13,465/2017) for enabling the legalization of prior illicit claims on public and undesignated public lands (known as *grilagem de terras*)[23,24,42]. Public land covers two types of conservation units – Integral Protected Areas, with very limited use options such as research and tourism, and Protected Areas for Sustainable Use, which allow e.g. renewable energy development within the subcategory Areas of Environmental Protection (APA). In addition, public land compromises Indigenous lands, Afro-Brazilian Quilombola areas, and rural settlement areas. Undesignated public land in our analysis refers to the residual area not covered by private or public land. According to the Federal Constitution (Art. 183, 191), undesignated public lands, also known as 'vacant lands' (*terras devolutas*), cannot be privately appropriated. However, the approval of multiple modifications and amendments to regulate private property have favored the legitimization of illegal appropriation and use of these areas at the expense of agrarian reform[4]. This phenomenon has been widely studied in the context of deforestation in the Brazilian Amazon[43,23,44], but the issue of undesignated public lands is increasingly linked to the loss of common lands and threats to collective use rights of traditional populations posed by the expansion of VRES[45,46,35].

We focus our analysis on identifying different schemes of land appropriation and claims for the expansion of wind and solar PV parks, rather than alternative land-uses. We use the following hierarchization of land tenure regimes: On private land, licit private property titles override CAR titles. Private claims to rural properties, both registered in the SIGEF and SICAR systems, also override public land classification. Undesignated public land covers the residual area of the former categories. Figure 1 illustrates in addition to the ownership and investor relationships, the land tenure situation of the Primavera wind park, which is composed of four different modes of land appropriation to gain control over the area: Private property titles (A)-(D), and a CAR title (E). The registered submission/approval dates from the SIGEF land tenure system reveals that the area was formally privatized in the years 2015-2016 after the first investment in the wind park (in 2012), clearly indicating that the development of the large-scale Primavera wind park (start of operation in 2018) is related to privatization activities. Here, a national-international ownership and international investment structure have significantly driven the dynamics of private land appropriation, with previously formally public or undesignated public land being fully privatized in one part and claimed by CAR title in another for wind turbine siting. Note that neither SIGEF nor CAR provide details on legal title holders, we therefore cannot provide information on royalty payments between landholders and wind park investors. In addition, other overlapping land claims may exist, including private property titles registered exclusively in local notaries. However, many of these legally disputed cases lack regulatory verification, which delays inclusion in the national SIGEF land tenure system and, subsequently, were not considered in our analysis.

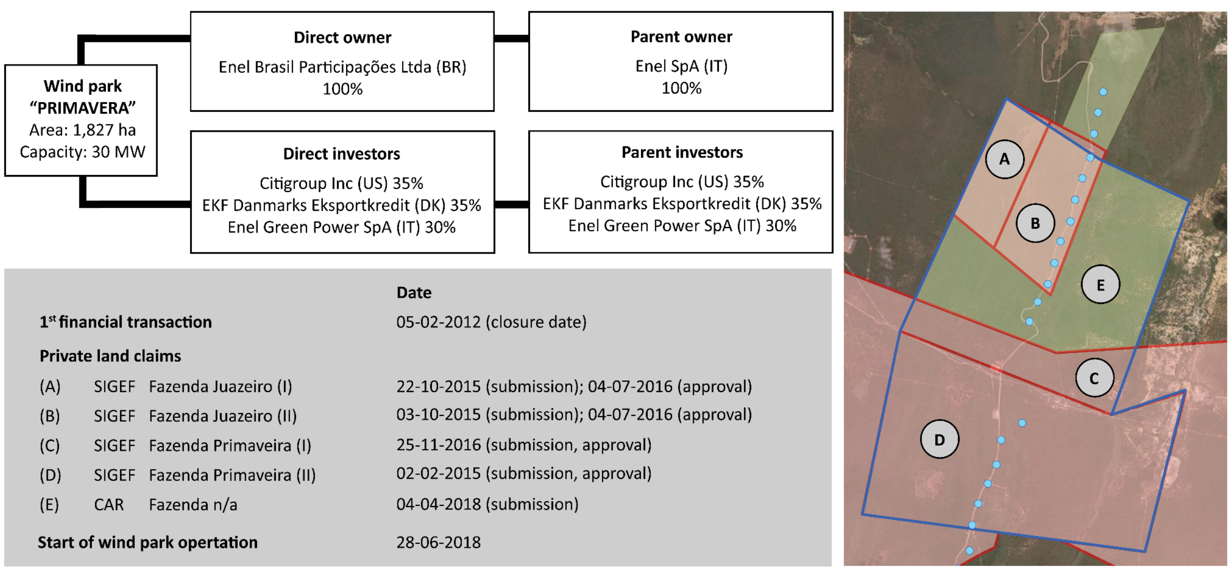

Figure 1. Wind park 'Primavera' (blue polygon) and turbines (blue dots) located in the municipality Morro do Chapéu, State of Bahia. Investors and owners (left above), temporal analysis of financial transactions and private land claims (left below), map with park boundaries and overlapping land tenure composition (right).

Results

Investment and ownership landscape of wind and solar PV assets

Measured by occupied area, foreign companies are involved, either as investors, owners, or both, in 78% of all wind parks and in 96% of all solar parks. This demonstrates the significant presence of international companies, either directly or through subsidiary relationships, in land appropriation of the renewable energy sector in Brazil. The individual contributions by region and type of financial participation differs quite substantially between technologies and is explored in the following.

Our database reveals that wind parks in operation and in construction cover an extensive land area of 2,148 km^2, primarily located in the northeastern region of Brazil. It is worth noting that this project area extends beyond the immediate land occupied by wind turbines and roads. Therefore in theory, there is potential for integrating wind parks with other land uses. However, in practice, access to land and its potential co-utilization are highly restricted by fences and controlled by armed security forces and watchtowers[35,47].

The majority of ownership associated with Brazilian wind parks is held by Brazilian entities. Specifically, direct ownership is predominantly Brazilian, covering 89% of the land (Figure 2), and the ten largest owners are all Brazilian entities (Supplementary Figure 1). However, within these Brazilian direct owners, seven are subsidiaries of foreign companies. As a result, a significant portion of parent owners can be traced back to foreign regions, encompassing approximately 68% of the total wind park area, the largest foreign parent owner being Enel SpA (Italy). Among the regions with foreign parent ownership, Europe stands out as the largest contributor, with European companies being associated with 52% of all wind park areas. France emerges as the leading foreign parent owner country, holding a 12% share of the total wind park area, with Engie SA being the largest French parent owner. Brazil retains the largest overall share, with 34% of all parent owners associated with the country.

Regarding investments, the majority of direct investors (88%) and parent investors (65%) come from Brazil. Among the top 10 direct investors in Brazilian wind parks, all are of Brazilian origin (Supplementary Figure 1). The investment landscape in Brazilian wind parks prominently involves the public Brazilian Development Bank (BNDES), which accounts for 15% of the land area. This highlights the significant involvement of the public sector in the development and financing of the wind power sector in Brazil. Approximately 87% of the parks associated with the BNDES, also have some form of foreign ownership or investments, indicating that foreign companies also benefit from state subsidized capital. Furthermore, certain Brazilian investors are subsidiaries of foreign companies. For instance, the second largest investor, Enel Green Power Brasil Participações, whose parks cover 7.5% of the land area, operates as a subsidiary of Enel Green Power SpA from Italy. Similarly, Volitalia Brazil, associated with 2.5% of the land area, functions as a subsidiary of EDP Renovaveis SA from Spain. Although the largest parent investment company comes from Italy, Spanish companies in total follow Brazil as a significant source of parent investments, occupying the second position with 10% of the overall land area. We do not find temporal trends in the participation of different regions in terms of ownership or investment in wind parks (Supplementary Figure 2).

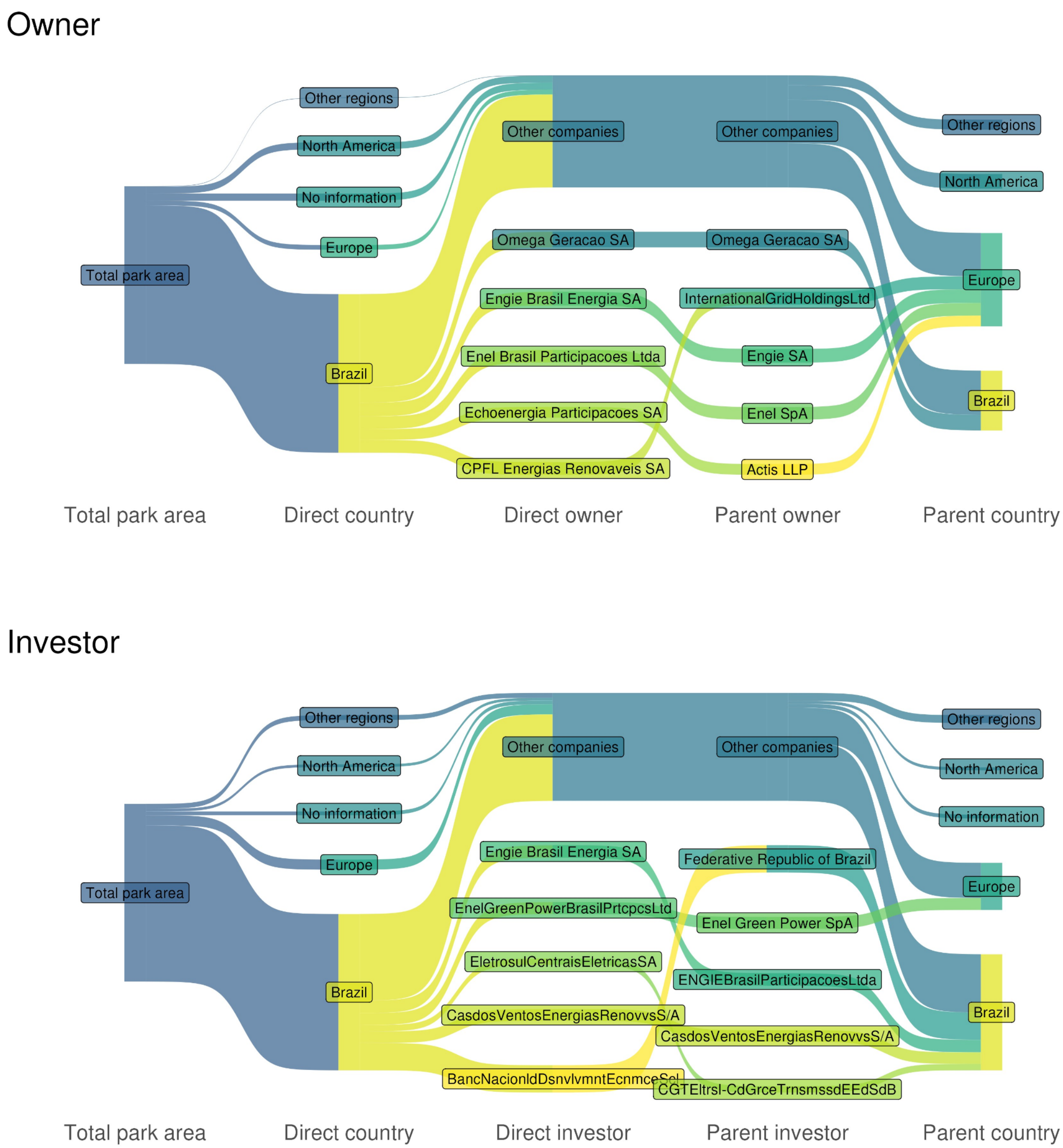

Figure 2: Sankey diagram of how wind park area is distributed by region and company for wind park owners (top) and wind park investors (bottom). Countries included in regions can be found in Supplementary Table 2.

The land area occupied by solar PV parks is smaller compared to wind parks. This is due to a combination of lower installed capacity and higher power density of solar PV in comparison to wind power.

Specifically, a total of 102 km^2 of land is utilized by 117 solar PV parks. Although the overall land area is significantly lower, the land-use intensity of solar PV parks is much more intensive compared to wind power[48]. This means that the potential for sharing land with solar PV panels for e.g. agricultural purposes, is limited due to the limited spacing area between panels and restrictive access. In terms of international involvement in renewable energy projects, solar PV exhibits a higher level of foreign participation compared to wind parks (Figure 3). Parent owners and investors largely originate from outside of Brazil, accounting for 90% and 74% of solar PV areas, respectively. Even 46% of areas associated with direct owners are non-Brazilian, while areas linked to direct investments are mostly Brazilian (85%). Similar to wind power, the majority of non-Brazilian parent investors and parent owners are from Europe (57% and 66%, respectively). Italy holds the largest area associated with parent ownership (27%), which is significantly higher than Brazil's area (10%), placing Brazil in fourth position in terms of parent ownership. Italy is also the top country in terms of parent investors, with 30% of the area linked to investments from Italy, while Brazil ranks second with a share of 26%.

Unlike wind power, the primary investment in solar PV projects in Brazil is driven by private entities. Two companies, Enel Brasil Participações Ltda and Enel Green Power Brasil Participações, both subsidiaries of Enel Green Power SpA from Italy, dominate the sector, being involved in 30% of the land area occupied by solar PV parks (Supplementary Figure 3). The second-largest player is the public bank Brazilian Banco do Nordeste do Brasil SA, accounting for 12.5% of the total area. Similar to wind power, the top 10 direct investors are Brazilian, with one exemption (Engie Solar SAS from France). However, all private Brazilian investors, except for one, are subsidiaries of international companies. In stark contrast to wind parks, the 10 largest direct owners of solar parks originate largely from abroad. For example, the second-ranked company, Actis LLP with a 12.5% land area, is from the UK, while CGN Energy International Holding from Hong Kong holds 10% of the land area. With one exemption, all parent owner companies are foreign, and the largest among them is Enel SpA from Italy, occupying 26% of the land area. We do not find temporal trends in the participation of different regions in terms of ownership or investment in solar parks (Supplementary Figure 4).

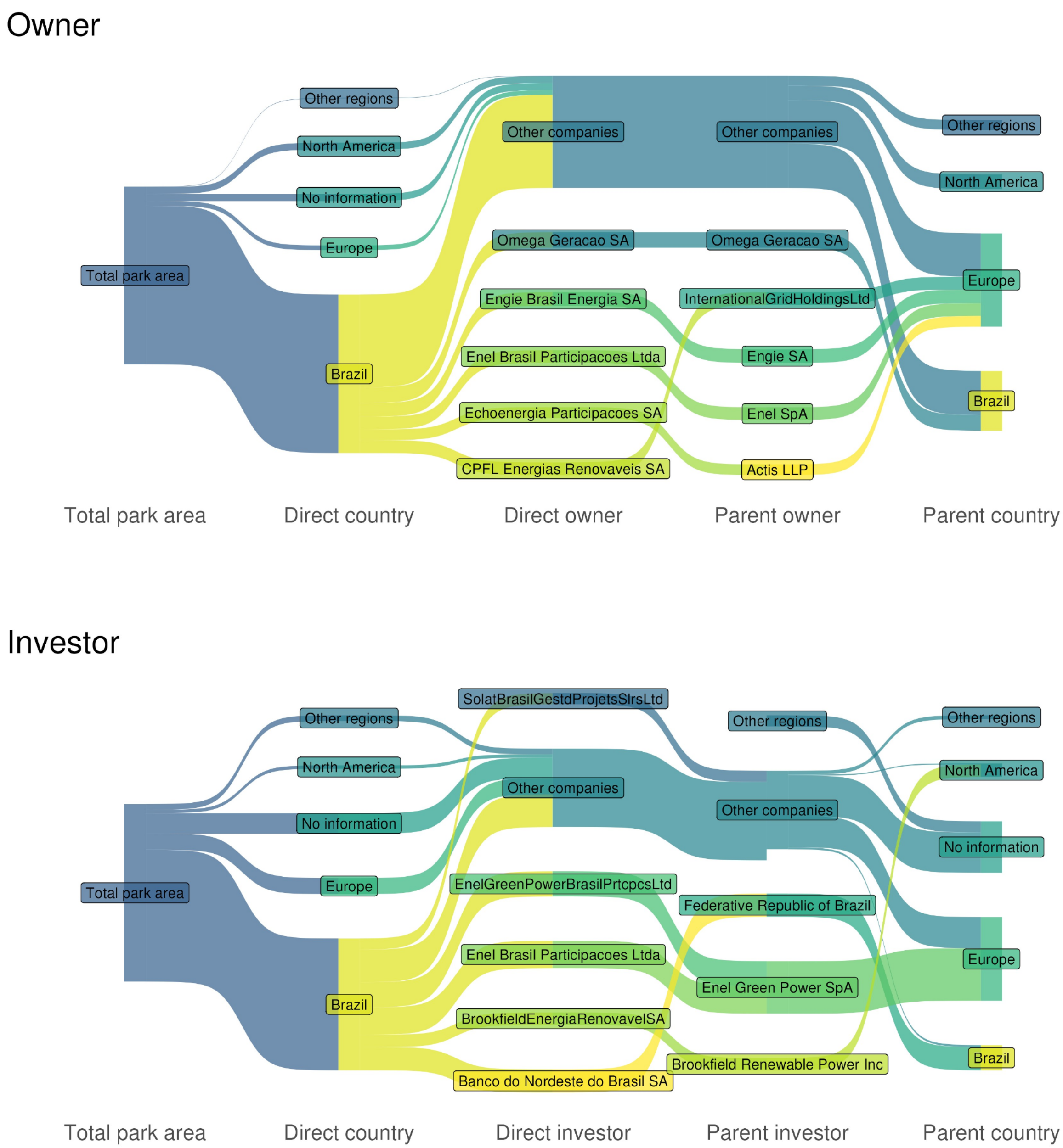

Figure 3: Sankey diagram of how solar PV park area is distributed by region and company for solar owners (top) and solar PV park investors (bottom). Countries included in regions can be found in Supplementary Table 2.

Wind and solar PV park areas by land tenure category

In the previous section, we have shown owners and investors involved in taking control of land for expanding VRES. Here, we analyze the prevailing modes of land appropriation in VRES park and control areas. The majority of land regulation in wind and solar PV parks consists of private land with legal property titles (64% and 96%, respectively) (Figure 4). Note that solar PV parks have a higher share of legal private ownership than wind parks. But in both groups, the total share of legal private property titles is significantly higher than in any of the control groups[1]: 21% and 28% of the area, respectively, of the two wind power control groups, i.e. *Control random* and *Control match wind resource,* is covered by legal private property titles, while for the control area for solar PV, this share is 47%, indicating that solar PV parks are located in municipalities with higher shares of legal private property titles than wind parks.

Note that the two control areas for wind parks, i.e. *Control random* and *Control match wind resource*, have different shares of legal private property titles. We identify two potential reasons: first, control areas of type *Control match wind resource* are placed closer to existing windparks, as they are found in locations with high wind speeds. Spillover effects of privatization from existing wind parks may cause the higher shares of private land there. Furthermore, these areas may also be interesting for future investments in wind parks and may therefore already see higher rates of privatization.

To statistically analyze, if a significant difference in land regulation patterns can be confirmed, we calculated the share of land regulation for each park and performed t-tests to compare the park areas with control areas for the four different land categories. Our analysis involved a sample of 574 wind parks and 44 solar PV parks, and the corresponding boxplots can be found in the appendix (Supplementary Figure 5). The purpose of the t-tests was to determine if there were significant differences in the means between the control areas and the park areas for each land category (private land with legal property title, private land with CAR title, public land, and undesignated public land), for both wind parks and solar PV parks. The p values of the t-tests are well below 0.001 when testing differences in mean between the park areas of wind parks and solar PV parks compared to all types of control areas, confirming that the groups have different types of land regulation patterns.

These findings clearly support that VRES park developers prefer private legal property titles over other forms of land tenure regulation. For wind parks, however, the composition of land tenure regimes is more diverse: 36% of the wind park area is not covered by private legal property titles. 28% of the land is only covered by CAR titles, i.e. by self-declared titles submitted to the rural environmental registry, which are commonly used as claims for controlling land, but are legally not binding. Furthermore, 8-9% of the total wind park area has no information on private ownership, and overlaps with some form of public land (2%) or undesignated public land (7%). In contrast, only very minor shares of solar PV parks are not covered by legal private property titles (4%).

Furthermore, we examined land regulation also for turbine locations only, excluding other areas of wind parks. We found that only 55% of all turbines are situated on land with legal private property titles, while 38% are located on private land with CAR titles only, and the remaining 7% overlap with public or undesignated public land. Therefore, private property titles are less present at locations of installed infrastructure.

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[1] For solar PV parks, there is one control group, a randomly chosen area in the same municipality of the same shape. For wind parks, there are two control groups: one randomly chosen area, and another area, where we match the wind resource quality of the wind park area to the control area.

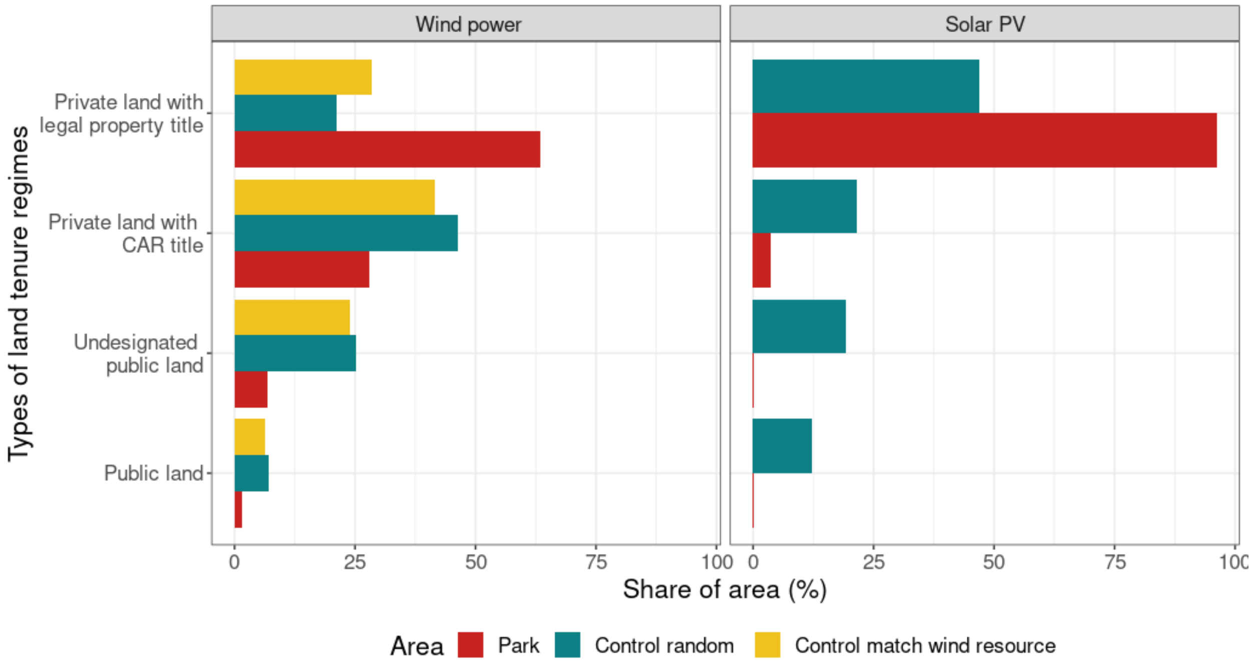

Figure 4: Land area by type of land tenure regime for wind power (left) and solar PV (right). Random areas are sampled from the same municipality with the same shape.

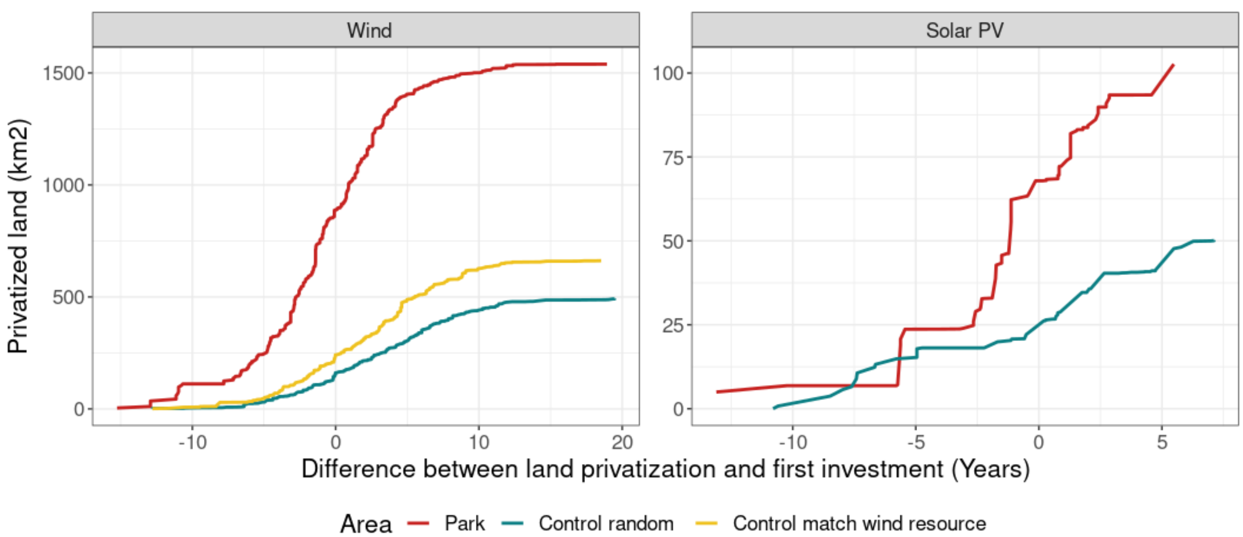

Figure 5: Cumulative land privatizations for wind parks compared to control areas as function of the difference in time to first investment. Wind parks (left), solar PV parks (right).

While we observe that VRES parks are built on higher shares of private land with legal property titles than found on control areas, does this imply that public or undesignated public land has been privatized for that purpose? We therefore also assessed the timing of land privatizations in relation to the first closure date of an investment in a park as a proxy of development activity (Figure 5), to determine if we can establish temporal proximity between investment and privatization activities.

We find that for both technologies, 75% of land privatizations took place later than 5 years before the first closure date of the financial transaction, and land privatizations have picked up in speed in the years around the closure date, indicating that large shares of land privatizations are directly linked to VRES park development. In particular, almost half of all privatizations in wind park areas and one-third of all privatizations in solar PV park areas have taken place after the first investment, further strengthening the case that land areas have been privatized because of wind park development.

Discussion & Conclusions

Major networks of international and national governments, and corporate entities are the primary source of funding and investment in wind and solar PV parks in Brazil, being involved in 78% of all wind parks and in 96% of all solar PV parks. These VRES projects are driving the appropriation of relatively vast tracts of land by large-scale financial capital, confirming the hypothesis of green land grabbing that supports a variety of forms of dispossession and mechanisms of control grabbing for environmental ends such as climate change mitigation. Notably, solar PV parks have a higher level of international participation compared to wind power projects. One hypothesis explaining the difference, especially in direct ownership and parent investment, is that wind energy in Brazil has a longer history of development, based on governmental support programs (e.g. PROINFA), and higher local content requirements than solar PV, incentivizing the participation of national actors in wind park operations[49]. Our analysis confirms that strong investments by Brazil's National Development Bank (BNDES) benefit both national and international actors, showing the tension between government's interest to attract international corporations through low-cost financing[28] and protect domestic priorities - which will eventually continue to intensify due to the change of local content requirements from 60 to 30%[49]. In this regard, our assessment contributes to questioning the strong focus on foreign investors in major land deals[31], and to highlighting the complexity of the multiscalar entanglement of ownership and investment interests.

Furthermore, our focus on land tenure sheds light on the indirect implications of VRES expansion associated with land control through privatization. We show that for solar PV parks the predominant form of control capture is rooted in private property titles. This is also true for wind power, but in this case different modes of land acquisition and control overlap, including the use of CAR titles to illicitly claim private land possession, or the construction of wind turbines directly on public or undesignated public land without any form of tenure regulation. In principle, the choice of land tenure regime is linked to large-scale investments in infrastructure, which creates incentives to secure the park area with legally binding private property titles. The difference in land tenure regulation between solar PV parks and wind parks cannot be explained by the fact that spacing areas for solar PV parks are low, while they are high for wind parks: about 40% of wind park infrastructure, i.e. wind turbines, is placed on land without private property titles. One reason may be that solar radiation in Brazil's target areas is much more uniform than wind resources, and project developers therefore have greater spatial alternatives for building solar parks, including the choice of regulated tenure with private land. Conversely, wind park developers may accept unregulated land tenure to secure sites with prime wind speed potentials. This may be a promising strategy given recent government agreements, such as the Normative Instruction No. 01/2020 in the state of Bahia with its aim to secure legal access to land for corporate interests by specifically providing "procedures for land regularization on state vacant lands [*terras devolutas*] with wind power generation potential"[50]. Further research is necessary to confirm this hypothesis, including qualitative assessments of investment activity in existing parks.

In any case, land privatization increases in close temporal relation to investments in VRES parks, indicating that VRES development is driving the modification of land tenure regimes, particularly the privatization of public and public undesignated land. However, we cannot statistically identify causality between investments and land privatizations. The reason is that our proxy for the start of VRES park development, i.e. the date of the first investment into the park, is of limited capability: park development and activities to secure land control may have begun well before investments, as strategic investors may be unwilling to commit resources to negotiation and due diligence resources until a project has been fully 'permitted', i.e., including site control through regulated forms of land ownership, grid access, or if there is confidence that this can be achieved within a reasonable timeframe[51]. The permitting phase is the most time-consuming stage in the project development cycle, lasting between 2 and 8 years[52]. After this phase, direct owners may negotiate a financial package with their strategic investors. Therefore, various forms of acquisition of public or undesignated public land may have occurred prior to the initiation of investment activities, and temporal attribution of explicit land privatizations to VRES development is therefore complex.

Our analysis here has some limitations related to data availability. In particular, the CAR dataset lacks a breakdown of registrations over time, which hampers our ability to accurately assess the temporal relationship between investments and private land claims. The short time period and clustered nature of these privatizations and investments further contribute to the limitations of our evaluation. Finally, our assessment relies on publicly available datasets, which are primarily based on digital tenure systems at the national level in Brazil. Besides the Federal digital land tenure systems, there are also State cadastres and local notary systems that maintain records of non-digitized private land possession and ownership claims. However, public access to this property-specific information in digital format is not available, and Brazil still lacks a comprehensive national territorial management system that fully integrates this detail of land tenure information. We also recognise the need to consider not only the precise geographic area of operational land deals, but also the broader implications in both quantitative and qualitative terms. This includes the significance of non-operational or 'failed' land deals[53] in the overall context of land deal-making.

Further research, including empirical fieldwork, is necessary to better understand the causality between VRES expansion and land tenure modification, particularly in relation to legalization of prior illegal land appropriation and falsification of land titles (known as *grilagem de terras*). This is also critical as our results suggest that the development of wind and solar PV increases land competition, potentially exacerbating forms of dispossession and conflicts over land. This occurs either through direct occupation and control over unregulated land tenure, or by claiming private ownership prior to use. Our quantitative approach cannot analyze the specific dynamics of interaction with competing territorial rights and land uses. Especially for northeastern Brazil, qualitative and fieldwork-based assessments by scholars and civil organizations have extensively shown that VRES projects can seriously endanger livelihoods and culture of traditional peoples and communities[7,35,45]. To protect the rights of marginalized rural populations, particularly with respect to the historical occupation and communal use of common lands[33], and to prevent land conflicts and reasons for opposition, governments and companies must recognize these negative impacts related to VRES.

Addressing green grabbing as a complex form of large-scale investment promoting private appropriation and subsequent dispossession of common land is therefore crucial for guaranteeing socially just low-carbon energy pathways. It requires a comprehensive approach that includes strengthening the legal frameworks by recognizing and respecting land tenure rights and establishing mechanisms for resolving land disputes. Improved land governance is also essential, involving the development of transparent and accountable systems that integrate information from various sources. Based on the experience of land grabbing in the Brazilian Amazon, accelerating the CAR validation process, including the removal of illicit registrations from the SICAR system[42], is also an urgent priority for improving land governance in the Northeast. This includes creating a national territorial management system that effectively manages land and resource data, and also incorporates the recognition of the rights of traditional peoples and communities, as set forth in the ILO Convention 169 of 1989 ratified by Brazil on 25 July 2002. Additionally, promoting community participation in decision-making processes, conducting comprehensive environmental impact assessments, and holding corporations accountable for their actions and investments are key steps. Strengthening international standards, such as the United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP) and the International Finance Corporation's Performance Standards, would enhance responsible land use and the protection of human rights. Finally, fostering collaboration and dialogue among stakeholders are also vital to effectively address green grabbing and protect the rights of local communities.

Methods

Study area. Our analysis covers the national scale of Brazil and focuses on implemented wind and solar PV parks in regions of the Northeast (Bahia, Ceará, Maranhão, Rio Grande do Norte, Sergipe, Paraíba, Pernambuco, Piauí), Southeast (Minas Gerais, Rio de Janeiro, São Paulo) and South (Paraná, Santa Catarina, Rio Grande do Sul).

VRES area. The spatial allocation of wind and solar PV infrastructure is based on data provided by ANEEL, the National Agency for Electric Energy, dated 04/02/2022. For both technologies only facilities with status ‘operating’ and ‘in construction’ are considered, solar PV parks only above 5 MW installed capacity are included. The georeferenced information on the wind park area is completed with wind turbine and power plant attributes. For solar, the ANEEL data is limited to point features. The spatial PV area information was therefore derived from OpenStreetMap Brazil and manually validated and completed using GoogleMaps.

Ownership and investment data. The Bloomberg New Energy Finance (BNEF) dataset reports transactions on wind and solar assets from 2000-2021. Three BNEF datasets were merged for this analysis:

1. The *projects* dataset contains details of wind projects. It provides key project information such as project capacity, commissioning and completion date, financing date, direct owner, parent owner and location.

2. The *organisations* dataset contains details of companies and organizations involved in developing and financing wind projects, such as their country and business description.

3. The *transactions* dataset contains details of transactions on projects such as the transaction date, type of finance, equity investors and debt investors.

The final dataset reports 25.5 GW of wind and 8.6 GW of solar capacity compared to the 21.2 GW of wind and 13.1 GW of solar capacity reported by IRENA[54]. The greater wind coverage reported in the BNEF data as compared to IRENA data is likely because the BNEF data includes information on wind assets that have secured finance but are not yet operational. The greater solar coverage reported by IRENA as compared to the BNEF data is likely due because BNEF does not report on projects less than 1 MW in size, which excludes rooftop solar installations accounted for by IRENA.

Merging ANEEL and BNEF data. To analyze park specific ownership and investment composition, we merged ANEEL solar and wind parks, dated 30/03/2022, with the BNEF dataset. Data merging is based on (a) fuzzy string matching on park names, (b) spatial locations, and (c) manual completion, in case that the spatial match and the string match did not agree or if there was no match at all. Finally, all matches were manually validated using public information on the internet. From 602 wind parks contained in Bloomberg, we could identify 574 matches in the ANEEL dataset. For solar PV, for the 120 solar PV parks listed in Bloomberg, 117 could be matched with ANEEL. However, these 117 parks are linked to only 44 shape files, as many parks were built in several phases, i.e. one large panel area (identified from satellite imagery) is possibly linked to several projects in the BNEF and ANEEL data sets. Each park is therefore allocated the same share of the total area, when several parks share one common area.

Areas were linked to investment following the following rules: for direct and parent owners, the share in land areas was equal to the share in ownership, given in the Bloomberg dataset. As not in all cases, the shares add up to one in the dataset, we determined a new share as the fraction of the share given in the database divided by the sum of all shares for that particular park, i.e. $share_i^{new} = \frac{share_i}{\sum_j share_j}$. For direct and parent investors, no detailed information about the share in investments is given. We therefore first split the area between equity and debt providers, according to a gearing ratio known on a national level (58% and 70% for debt providers, for solar PV and wind power projects respectively). Within these categories, land areas were split evenly between all investors.

Land tenure analysis. Due to the lack of reliable nationwide integral dataset of rural properties[4], the land tenure analysis builds on various publicly available datasets (Supplementary Table 1). In addition, we aligned our methodological approach with Imaflora's most recent dataset, the Brazilian Agriculture and Ranching Atlas (Atlas da Agropecuária Brasileira, or ATLAS, v.181217[55]). The ATLAS dataset combines multiple public data sources and uses an expert-vetted system to systematically resolve data conflicts resulting from, e.g., overlapping land claims due to illicit land title fraud or mapping error[5]. However, the ATLAS dataset lacks information on the date of land claim registration in SIGEF/SNCI and CAR registries. We therefore use rural property information from the public SIGEF and SICAR systems, dated 12/1/2022, but similar procedures to clean the original data, outlined in Supplementary information 2. Furthermore, we applied a similar prioritization scheme based on the level of legal security of the rights, geospatial precision, and the likelihood of transition from public to private status, whenever overlapping land tenure information is found: private property titles registered in SIGEF and SNCI have highest priority (Figure 6). CAR titles have the second highest priority, i.e. private property titles are erased from CAR titles. Public land, including rural settlements, Afro-Brazilian Quilombola lands, Indigenous lands, and conservation units in both the Integral Protected Area, and Protected Area for Sustainable Use categories has the lowest priority: both private property and CAR titles are erased from the respective shape files of public land categories. Finally, any area in the municipalities of interest, i.e. the ones with wind or solar PV parks installed, which is not covered by any of these three land tenure categories, is classified as undesignated public land.

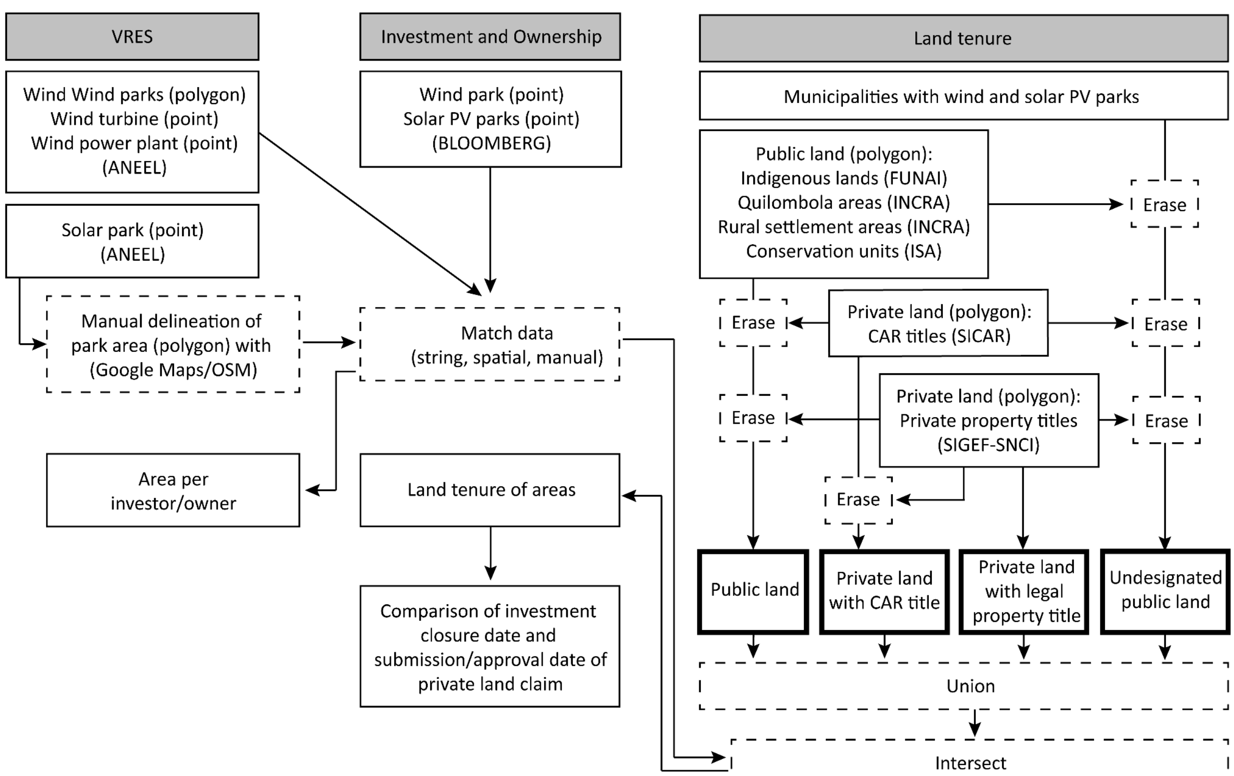

Figure 6. Model for processing the land issue in wind power and solar PV development

Control areas. For each park, we randomly sampled 100 points from the same municipality as the respective park is located. We then rotated the shape of the park 100 times randomly and moved one shape to one of the 100 random points. Those shapes which did not overlap with existing wind or solar PV parks and which were spatially completely contained in the municipality, were selected subsequently. In total, we had 124,000 km^2 to sample from for wind parks and 72,400 km^2 for solar PV parks. From the set of available parks, one was chosen randomly as control area (*Control random*). However, it may be that areas with good wind resources may be structurally different from other areas, even if no wind parks have been built there. For example, such areas are often on mountain ridges. As a simple matching procedure, we therefore created an additional control group (*Control match wind resource*), controlling for wind power density: from the sample of available control areas, we chose the area with the lowest absolute difference in wind power density to the reference wind park area. Wind power density is calculated from the Global Wind Atlas version 2.3[56]. We did not control for solar radiation for solar parks, as it is very uniformly distributed within municipalities. Supplementary Figure 6 illustrates the procedure.

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Supplementary information 1 - tables and figures

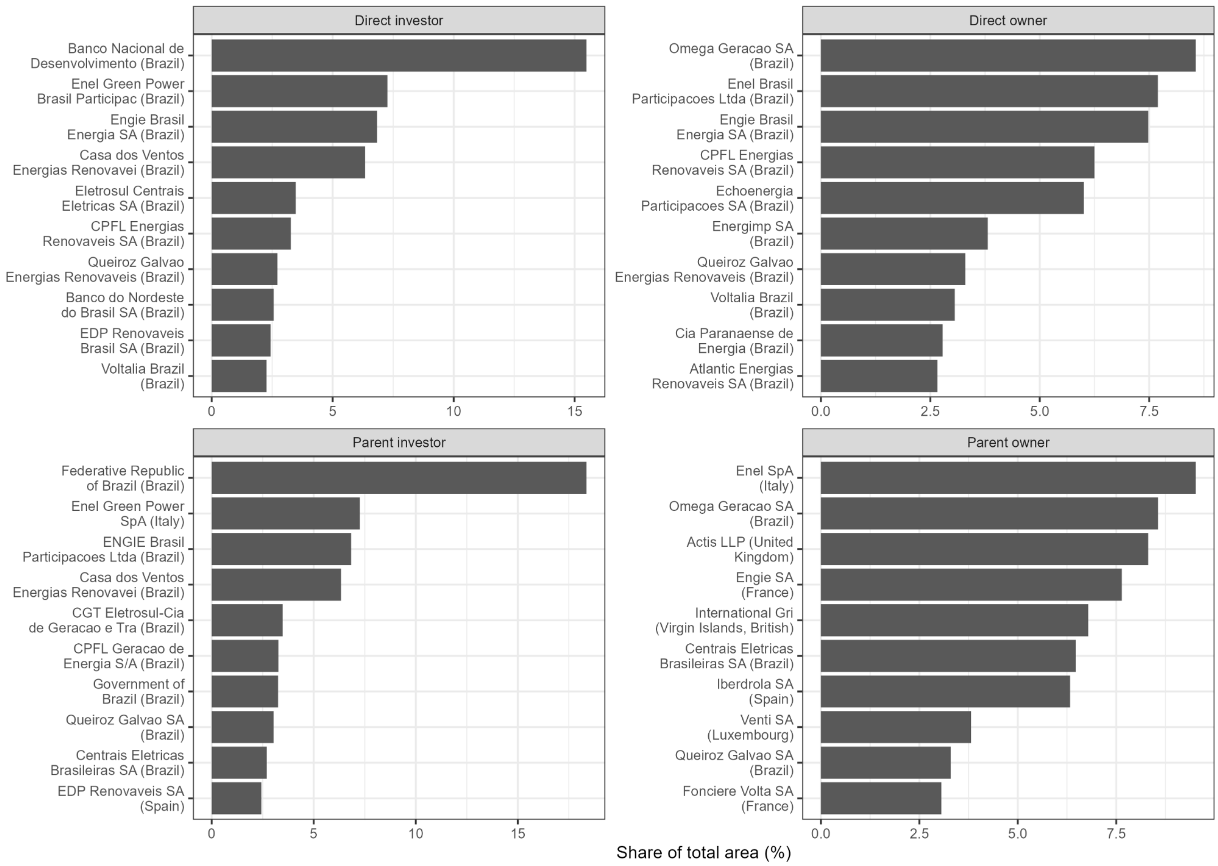
Supplementary Table 1. Dataset of the digital land tenure system

Core land tenure-regime	**Land tenure category and description**	**Source**	**Date of acquisition**	**Period covered**
Private land	Licit private property titles: Privately owned properties are registered in the Sistema de Gestão Fundiária (SIGEF) or Sistema Nacional de Certificação de Imóveis (SNCI). The certification of the georeferencing of rural property ownership, created by Law 10.267 of 2001, is carried out exclusively by Incra, and guarantees that the georeferencing complies with legal technical standards and specifications. We considered the names and boundaries of the rural properties as well as the date of submission and/or approval.	SIGEF and SNCI-INCRA	12-01-2022	> 2022
	CAR titles: According to Brazilian Forest Code (Law 12,651/2012), geo-referenced private rural property information must be submitted to the public electronic registry Sistema Nacional de Cadastro Ambiental Rural (SICAR). We only considered property boundaries and submission dates.	SICAR-MMA	12-01-2022	2022
Public land	Indigenous lands: Legally defined area owned by the Union, aimed at preserving indigenous communities.	FUNAI	12-10-2021	> 2021
	Quilombola areas: Rural properties occupied by Afro-Brazilian communities of descendants of fugitive slaves from the colonial period.	INCRA	12-01-2022	> 2022
	Rural settlement areas: Agrarian reform areas composed of small-scale agricultural plots.	INCRA	12-01-2022	> 2022
	Conservation units: Differentiation according to ecological protection status – i) Integral Protected Areas (strict protection); ii) Protected Areas for Sustainable Use (with options for anthropogenic land use).	ISA	03-03-2021	> 2021
Undesignated public land	Vacant lands (known as *terras devolutas*): Undesignated or untitled public lands owned by	Estimated result	n/a	2022

	the Union or States, but often historically occupied and used by traditional communities, as well as affected by land grabbing and resource extraction.	based on the spatial analysis		
Administrative	Municipality borders	IBGE	18-01-2021	2020
	State boundaries	IBGE	18-01-2021	2020

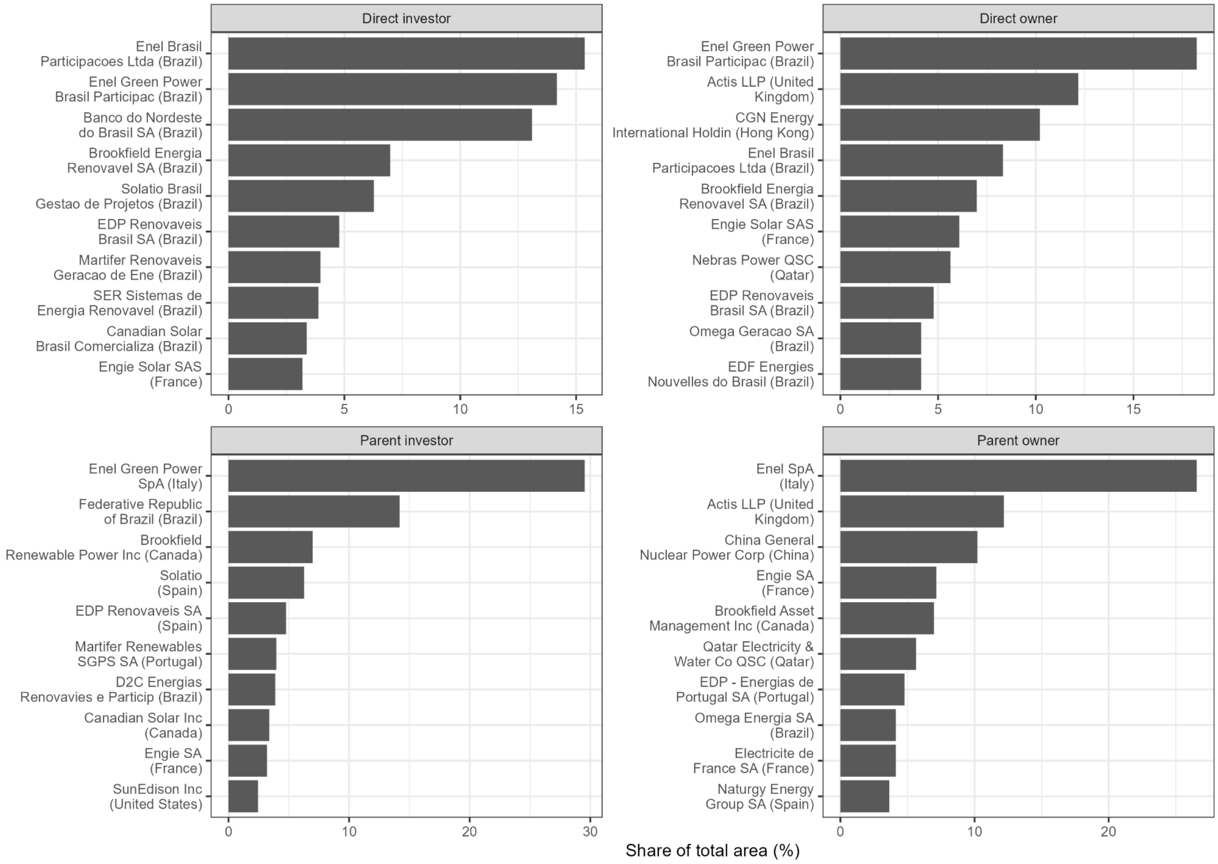
Supplementary Table 2: Countries in regional groups

Technology	**Region**	**Included countries**
Wind	Brazil	Brazil
	North America	United States, Canada
	Europe	British Virgin Islands, Denmark, France, Germany, Isle of Man, Italy, Luxembourg, Portugal, Spain, Sweden, United Kingdom
	Other	Argentina, Australia, Bahrain, China, Colombia, Hong Kong
Solar PV	Brazil	Brazil
	North America	Canada, United States
	Europe	British Virgin Islands, Denmark, Germany, Hong Kong, Isle of Man, Italy, Luxembourg, Portugal, Spain, Sweden, United Kingdom
	Other	Argentina, Australia, Bahrain, China, Colombia, Hong Kong, Qatar

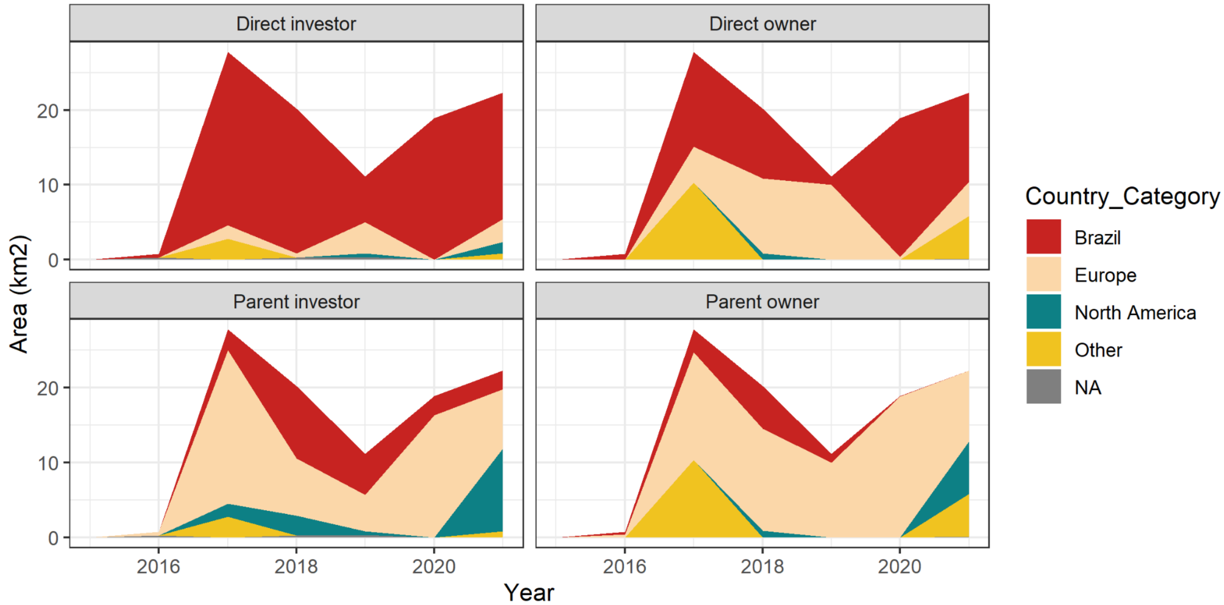


Supplementary Figure 1: Share of total land area occupied by wind parks per company

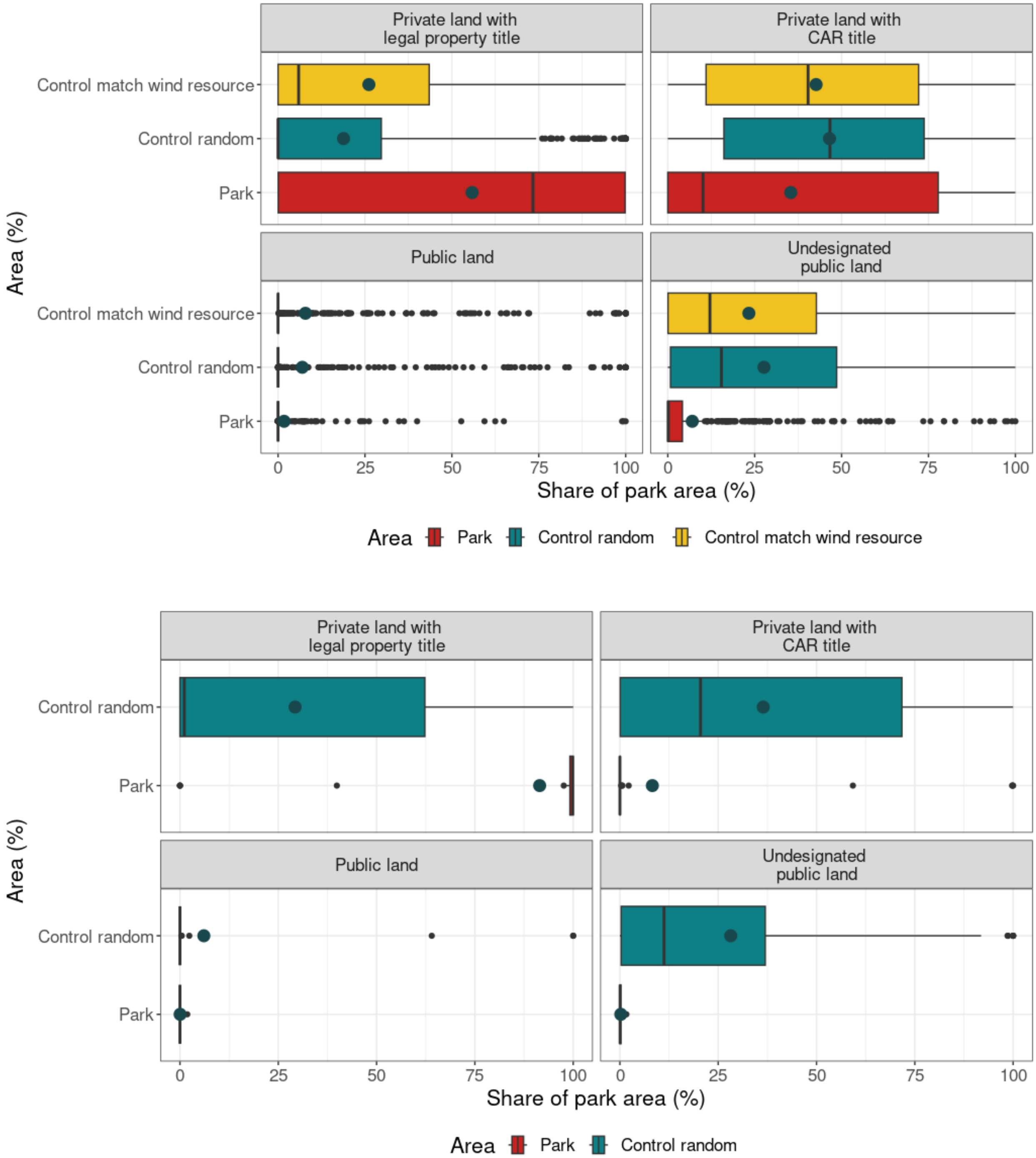
Supplementary Figure 2: Land area occupied by wind parks per investment and ownership country. Year indicates the start of park operation. Countries included in regions can be found in Supplementary Table 2.



Supplementary Figure 3: Share of total land area occupied by solar PV parks per company



Supplementary Figure 4: Land area occupied by solar PV parks per investment and ownership country. Year indicates the start of park operation. Countries included in regions can be found in Supplementary Table 2.



Supplementary Figure 5. Boxplots wind and solar PV park areas related to land tenure categories

Supplementary Figure 6: Example random sampling procedure for wind park Guirapa in the municipality Guanambi. The red shape is the original wind park. The green shapes are other wind or solar PV parks in the municipality. The points are 100 randomly chosen locations, the shapes surrounding the points are rotated and shifted shapes of the original wind parks on those points. Shapes which intersect with existing parks or which are not spatially fully contained in the municipality are removed. From the remaining shapes, a random shape is chosen (in orange) for the group of *Control random* areas. For the group *Control match wind resource* the shape is chosen, where the absolute difference between the mean wind power density of the original wind park in red and the mean power density of the shape is minimized.

Supplementary information 2 - Cleaning GIS data

Land tenure data

We follow the methods introduced by ATLAS[55] to clean the GIS data, and inform here in detail about the performed steps. QGIS 3.28 and Python 3.9.13 with Geopandas were used to clean the GIS data. Although the data cleaning processes for CAR and SIGEF/SNCI data are very similar, the data quality of SIGEF and SNCI Data is by far better. Due to overlaps and erroneous geometries more than 50% of CAR area is lost during data cleaning, while the SIGEF/SNCI data set loses less than 5% of area.

CAR data

The Rural Environmental Registry CAR dataset was downloaded from the official Brazilian website at the end of 2022. As the dataset has to be downloaded for each district individually, only those from districts intersecting with the solar and wind plants were used (i.e. 132 municipalities). To clean the data, the 132 CAR shapefiles were merged to one large Geodatabase. The polygons that intersect with wind and solar parks were selected with *select by location* and duplicate geometry was removed. Furthermore, duplicates in the column COD_IMOVEL, i.e. the CAR registration code, were removed, prioritizing larger areas over smaller ones. To remove polygons with unnatural shapes, the CI (circularity index) was calculated according to the following formula: $CI = \frac{2\sqrt{\pi A}}{P}$, A being the area and P the perimeter. Polygons with CI smaller than 0.12 and polygons with a CI bigger than 0.98 were removed. This rule does not affect final outcomes significantly. Furthermore, polygons that contain more than 5 Polygons within their boundaries were removed. The total CAR area resulting from our analysis is in particular sensitive to this rule, as very large CAR titles are removed from the data set and total CAR area therefore is reduced.

The CAR dataset was divided into poor and premium quality: premium polygons have less than 5% overlap with other CAR polygons and are therefore more trustworthy. Polygons with poor quality have more than 5% overlap with other CAR titles and therefore possibly lose a significant amount of area in the following cleaning process. If there are overlaps, premium CAR titles are prioritized over poor CAR titles. Within the two categories, overlaps were removed randomly. At the end polygons smaller than 1 ha were removed. Note, as we do not use CAR title specific meta-information, the order of prioritization of CAR titles does not affect our results - they are therefore insensitive to the particular choices made in these final steps.

SIGEF/SNCI data

SIGEF and SNCI polygons are both representing rural properties in Brazil. Therefore they were merged, keeping the certification date. Duplicate geometry was removed. Again, shapes with unnatural CI (see above) were removed. Overlapping geometry was also removed, prioritizing titles with the most recent certification date.

Wind park data

Wind park data was of high quality in general, but a minor share of wind parks showed overlaps. We removed them, prioritizing the area of the wind park with the most recent operating date.