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Effects of Climate Change on the Distribution of Key Native Dung Beetles in South American Grasslands

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Abstract: Climate change is a serious threat, and it is necessary to prepare for the future climate conditions of grazing areas. Dung beetle species can help mitigate global warming by contributing to intense nutrient cycling and reduction in greenhouse gas emissions caused by cattle farming. Additionally, dung beetles increase soil quality through bioturbation and reduce nematodes and hematophagous flies' abundance in grasslands areas. There are several dung beetle species inhabiting South American pastures, however, the effects of climate change on their spatial distribution are still unknown. Here, we aimed to predict the potential effects of future climate change on the geographical spatial distribution of the four most important ("key") pastureland dung beetle species that are native to South America. We used niche-based models and future climate simulations to predict species distribution through time. Our findings show radical reduction in the spatial range of dung beetle species, especially in recently opened areas, e.g., the Amazon region. We suggest that the consequences of these species' spatial retraction will be correlated with ecosystem services depletion under future climate conditions, urgently necessitating pasture restoration and parasite control, as the introduction of new alien species is not encouraged.

Keywords: livestock; grassland; Amazon; global warming; Scarabaeinae

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1. Introduction

Grassland environments need a number of active ecosystem services in order to maintain their herd capacities and both economic and ecological sustainability. Ecosystem services are benefits that ecosystems naturally provide and people take advantage of. Diversity and ecological benefits are positively related [1,2], which means that the higher number of species in a certain place increases the possibility of different niches, likewise increasing the possibilities of providing ecosystem services [3].

The current biodiversity loss is directly affected by species extinctions derived from deforestation and climate change [4,5]. Landscape modification, habitat conversion, and climate change are strong drivers for biodiversity losses and changes in correlated ecosystem services [6,7]. The effects of future global warming are clear, species spatial distributions may move to higher altitudes and latitudes towards suitable environmental conditions [5]. Under the future spatial redistribution, it is common that species reduce their area of occurrence [8,9]. Moreover, different species compositions can be formed as a result of species spatial redistribution [5,10], and yet these new communities are unknown, as well as the correlated ecosystem services provided by them. The understanding of the effects of climate change on ecosystem services provided by key species is crucial to the conservation of service provision and political decisions, mainly in highly impacted regions and/or countries with high deforestation and biodiversity loss.

Brazil is a continental country that occupies much of South America; it has one of the greatest beef cattle herds in the world, and the second biggest commercial production [11]. The beef cattle market in Brazil represents 30% of the national income in agribusiness. The costs to maintain this productive and successful chain are extremely high, especially with regard to animal nutrition and veterinarian care. The economic loss to Brazilian livestock production due to cattle parasitism is approximately USD 13.9 billion per year, of which USD 10.35 billion is due to gastrointestinal nematodes and horn flies [12]. Both gastrointestinal nematodes and horn flies have a stage of their life cycle in cattle dung, thus the more dung available in pastures, the more parasites likely to exist in that area. To study species that are related to this level of food security is of the highest importance to create a sustainable production system.

The burial of cattle feces is an extremely valuable ecosystem service for pastures that is directly dependent on the presence, abundance, and diversity of dung beetle species [13–15]. Dung beetles are insects of the subfamily Scarabaeinae (Coleoptera, Scarabaeidae) that feed and nest on mammal feces and other decomposing material [16]. By mixing and incorporating organic matter into the soil, dung beetles promote bioturbation, enhancing soil physicochemical characteristics, and consequently, the growth and nutritional value of plants [17,18]. The role of dung beetles in pastures also has economic benefits, as they minimize the cost of pharmaceuticals to control nematodes and hematophagous flies [19,20]. Additionally, there is a reduction in the amount of greenhouse gas emission of 7% in dung pads and 12% in pasture ecosystems—mostly related to methane CH4 that forms in anaerobic conditions and is reduced through oxygenation of pads from dung beetle activities [21,22].

More than 70 dung beetle species are reported to occur in South American grassland areas, but only a few are both highly frequent and broadly distributed, and these few are considered of the highest importance to ecosystem services in Brazilian pastures [23]. These key species are *Digitonthophagus gazella* (Fabricius, 1787), *Dichotomius nisus* (Olivier, 1789), *D. bos* (Blanchard, 1843), *Ontherus appendiculatus* (Mannerheim, 1829), *Onthophagus ptox* Erichson, 1847, *Trichillum externepunctatum* Preudhomme de Borre, 1880 and *Canthon lituratus* (Germar, 1813) [23]. Here, we aimed to predict the potential effects of future climate change on the spatial distribution of four of these species: *D. nisus*, *D. bos*, *O. appendiculatus*, and *T. externepunctatum*, those are, among the key species, the only four that combine both good present taxonomic status (no problems of misidentification), expansive spatial ranges, high local abundances and are native to their present range. *D. nisus*, *D. bos*, and *O. appendiculatus* are paracoprid (tunneller) species, this means that they bury feces deep below the dung pad; *T. externepunctatum* is an endocoprid (dweller) species, living inside the dung pad and disintegrating feces from the inside. We did not include the introduced African species *Digitonthophagus gazella* in our analysis because it has been studied before [24]. We also provisionally use the predicted presence of those main species as a proxy for the number of dung beetle species that likewise provide ecosystem services in priority areas for grazing intensification. As grasslands and pastures are somewhat similar to savannas and prone to be drier under future climate conditions [25], we expect a reduction in the spatial distribution, a possible depletion of correlated ecosystem services provided by these dung beetle species, and a reduction in the number of species per location providing services.

2. Materials and Methods

2.1. Dung Beetles Data Source

Occurrence records were obtained from the CEMT database (Setor de Entomologia da Coleção Zoólogica da Universidade Federal de Mato Grosso), by far the biggest dung beetle collection in South America, and published revisions: *Ontherus appendiculatus* [26], *Trichillum externepunctatum* [27], *Dichotomius bos* [28], and *D. nisus* [29]. All occurrence records with an absence of date and/or spatial site information, duplicate data, and centroid coordinates of municipalities were excluded. We compiled a total of 995 (*D. bos*, 225 records; *D. nisus*, 202; *O. appendiculatus*, 298; *T. externepunctatum*, 270) occurrence records for the 1970–2019 period, which were mapped to a 2.5-min grid (approximately 4.5 × 4.5 km resolution at the Equator).

2.2. Climatic Variables and Future Climate Simulations

We constructed a niche-based model to infer climatic processes driving the species spatial distribution. To characterize the environmental climatic space of the niche model, we used the 19 bioclimatic variables available in the WorldClim database v. 1.4 [30], at a spatial resolution of 2.5 min cell size (approximately 4.5 × 4.5 km resolution at the Equator). Because their variables are derived from temperature and precipitation, they are correlated to each other, requiring a variable selection process to decrease multicollinearity among the variables [31]. Here, we applied a factorial analysis [32] with a maximum rotation that resulted in five variables: Annual mean temperature (Bio 1), mean diurnal range (Bio 2), isothermality (Bio 3), precipitation of wettest quarter (Bio 16), and precipitation of driest quarter (Bio 17). To test the effects of future climate on the potential spatial distribution of species we used future climate simulations for 2050 (the midpoint for the period 2041–2060) and 2070 (the midpoint for the period 2061–2080) from the IPCC AR-CMIP 5/RCP 8.5 emission scenario: maximum power requirement, balanced emissions from fossil fuels and non-fossil fuels [33].

2.3. Niche-Based Model Building

We used a niche-based model approach to test the effect of future climate change on the dung beetle spatial distributions. The models were generated using the "dismo," "raster," and "kernlab" packages in the statistical programming software R [34–37]. As the combined use of multiple niche-model algorithms increases the accuracy of predictions by considering different niche estimates [38,39], we used the mathematical algorithms of presence only, and presence and background categorizations: (i) Bioclim (Envelope Score; [40]), (ii) Domain (Gower Distance; [41]), (iii) Mahanalobis distance [42], (iv) Random Forest [43], (v) Maximum Entropy (MAXENT v3.3.3 k; [44], e (vi) Support Vector Machines (SVM) [45].

To evaluate the model performance, we randomly subdivided the occurrence records into k-fold (2) subsets: training (consisting of 75% of the records) and testing consisting of 25% of the records). We repeated this procedure 10 times, resulting in 60 models. For each model, we calculated the maximum specificity and sensitivity threshold (Max Sens Spec), following [46], to calculate the True Skill Statistics (TSS) values as model evaluation. The TSS values vary from −1 to 1, with values above 0.4 representing good-fit models. Afterward we ran the ensemble forecasting approach to overlap all maps into a final map [47]. We used the approach of [31] that set the "10-percentile threshold" (10 PT) as a decision threshold rule, which makes the distinction between suitable (≥10 PT) and unsuitable (<10 PT) areas. We ran the models separately for each species. The models were built in the current climate conditions and projected for each future climate scenario.

2.4. Priority Areas for Livestock Intensification in Brazil

We considered priority areas for livestock intensification as those defined by Barbosa et al. 2015 [48]; this work defined priority areas only for Brazil. The definition and evaluation of these areas were based on (a) reduction in pasture areas as a result of agricultural expansion, (b) herd demographics, (c) logistics to major slaughterhouses, and (d) proximity to grain-producing areas. The priority areas were classified in minimum, low, intermediary, high and maximum priority (Figure 1). The spatial layer data of priority areas for livestock intensification in Brazil has a resolution of 0.5 × 0.5 km.

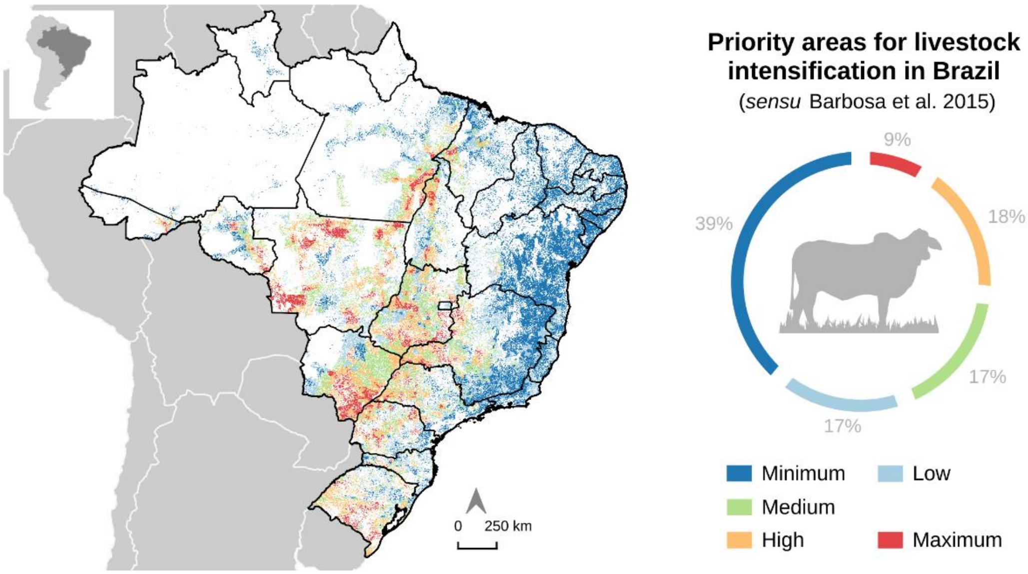

Figure 1. Priority areas for livestock intensification in Brazil *sensu* Barbosa et al. 2015 [48].

2.5. Effects of Climate Change on Key Dung Beetle Species Spatial Distributions and Livestock Priority Areas

To test the hypothesis of future dung beetle species loss in important priority areas for beef cattle intensification, we summed binary presence/absence maps of dung beetle species in each climate scenario to obtain maps of the number of dung beetle species (varying from 0 to 4) in Brazil. As the livestock priority areas have higher spatial resolution than species distribution maps, we resample the species maps by livestock priority areas by the mean using the 'resample' function of the *raster* R package [35]. We then used the Friedman test to assess the significance of the change in the number of species across climate scenarios in each livestock intensification priority class. Despite the large number of individual cells (~10 million pixels), we construct each Friedman test using 1000 times of 1000 random pixels to reduce the computational demand and because *p*-values are strongly correlated with the number of samples. We also calculated the effect size of the Friedman test using Kendall's W, which varies from 0 (indicating no relationship) to 1 (indicating a perfect relationship) with interpretation guidelines of 0.1–<0.3 (small effect), 0.3–<0.5 (moderate effect) and $\geq$0.5 (large effect) [49]. Note that Kendall's W is not affected by the number of samples. The same process was applied to identify the pairwise difference of scenarios with the Wilcoxon paired test with an effect size *r*, calculated as the Z statistic divided by the square root of the sample size.

2.6. Effects of Climate Change on Extent of Occurrence and Area of Species Occupancy

To test latitudinal and altitudinal shifts in species spatial distribution for each future climate scenario, we used the values of latitude (decimal degrees) and elevation for each site and the predicted presence of species for each climate scenario (present, 2050 rcp 8.5 and 2070 rcp 8.5). We used nonparametric Kruskal–Wallis tests followed by a post hoc Dunn test, to test if dependent variables (latitude and elevation) differ between times (present, 2050 rcp 8.5 and 2070 rcp8.5). To identify the magnitude of shifts over time in dependent variables we use the effect size measured by the eta-square (η2) value provided by the Kruskal–Wallis test. The eta-squared estimate assumes values from 0 to 1 and when multiplied by 100 indicates the percentage of variance in the dependent variable explained by the independent variable, the interpretation values are: 0.01–<0.06 (small effect), 0.06–<0.14 (moderate effect), and $\geq$0.14 (large effect).

Additionally, we calculated the area in km^2 for species present in each climatic scenario. The elevation and slope values were obtained through the EarthEnv Digital Elevation

Model (http://www.earthenv.org/DEM, accessed on 14 July 2021). The Kruskal–Wallis was built using the "kruskal.test" function of stats R package [37], the Dunn Test was calculated with "dunnTest" function with Bonferroni *p*-values adjustment within the FSA R package [50]. Graphics were generated using the "ggplot" function from the ggplot2 package [51]. All analyses were performed in the R program [37] considering a significance of $\alpha < 0.05$ and map projections were performed in the Qgis program [52] (QGIS Development Team 2020).

3. Results

3.1. Key Dung Beetles Spatial Distribution in the Present

Our models were all well fitting (TSS values > 0.4) (Figure S1). The geographic occurrence of the four species is similar, following a wide distribution in tropical dry areas and savannas of South America (Ecoregions: Llanos, Caribe lowlands, Chaco, Cerrados—including Pantanal, Caatinga, Pampa [53], and pastures) (Figure 2). The Andes limit their distribution to the west, while Patagonia is the limit to the south (Figure 2). None of them are found in forests, but they are present in open areas caused by deforestation of some regions of the Amazon and Atlantic Forest.

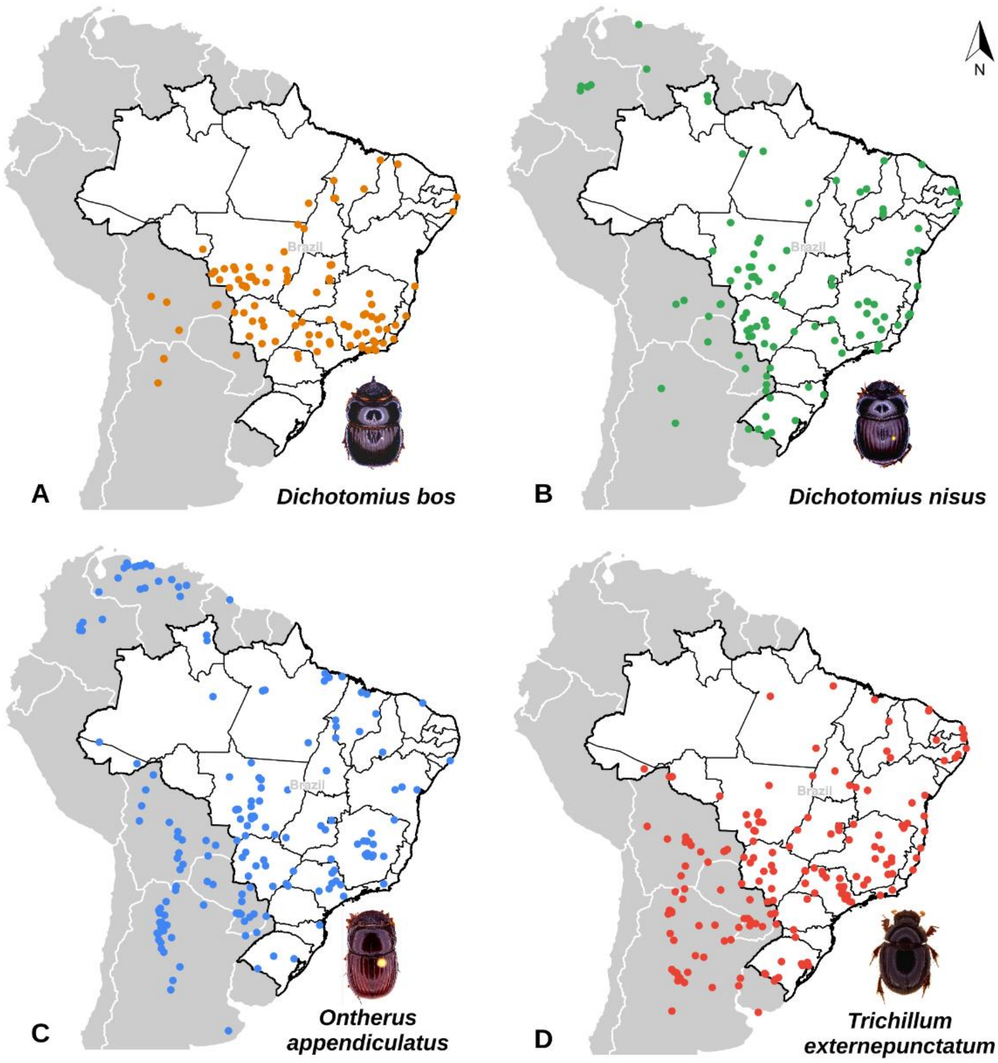

Figure 2. Geographical distribution of (**A**) *Dichotomius bos*, (**B**) *Dichotomius nisus*, (**C**) *Ontherus appendiculatus*, and (**D**) *Trichillum externepunctatum*. Data retrieved from specimens deposited at CEMT and literature (1970–2019).

Dichotomius nisus and *Ontherus appendiculatus* are found in open areas both south and north of the Amazon River (Figure 2). *Dichotomius bos* and *Trichillum externepunctatum* are not found north of the Amazon River, their northern range limits being the savanna enclaves south of the Amazon (Figure 2). None of those are present in ombrophilous forests.

3.2. Effects of Climate Change on Key Dung Beetles Range

The four species presented a reduction of 50% or more in their occurrence areas between the present and the 8.5 RCP 2070 scenario (Figure 3) and there is no expansion into new areas (Figure 3).

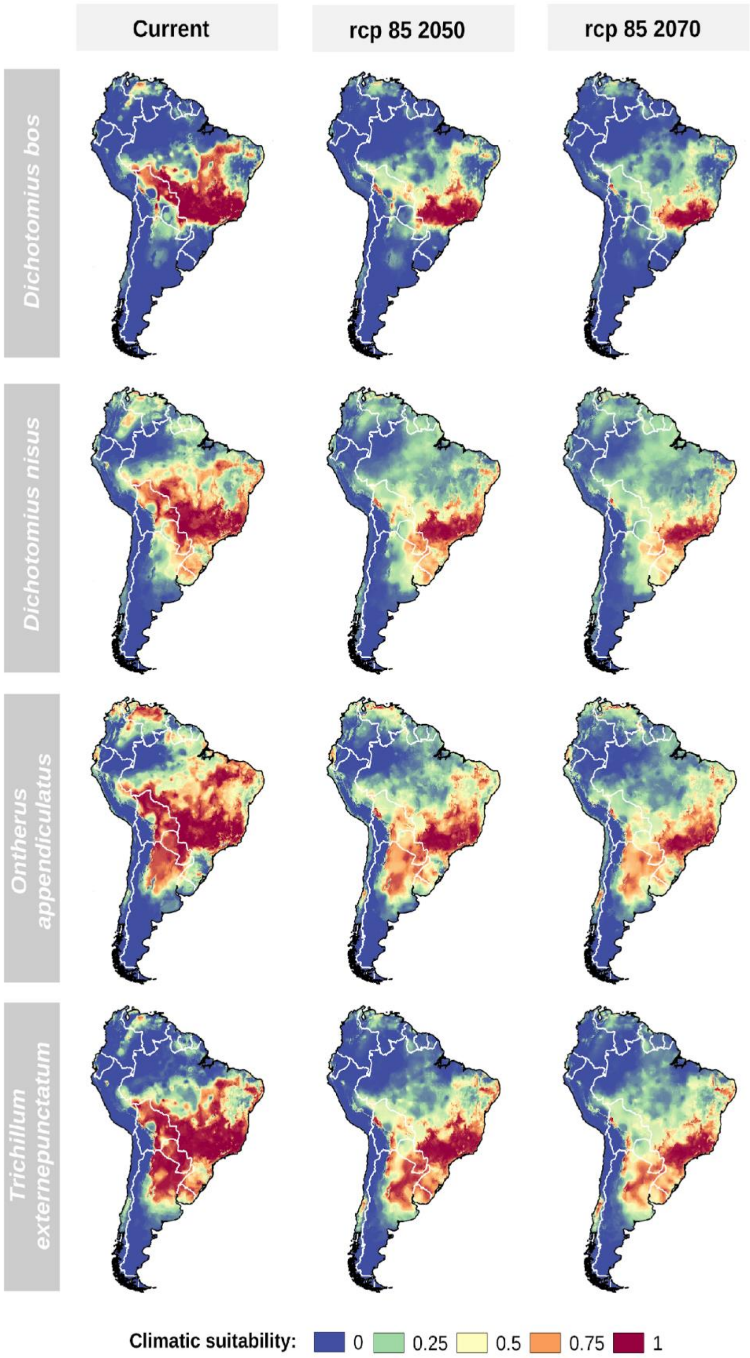

Figure 3. Niche-based models for present and future climate projections of 8.5 RCP 2050 and 2070 for four dung beetle species in South America.

Dichotomius bos has the worst scenario among key species. Our projections show a reduction of 70.7% in its area of occurrence by 2070, from 3,076,729 km^2 in the present to 1,387,037 km^2 and 904,217 km^2 in 2050 and 2070, respectively. *Dichotomius nisus* may lose 52.6% of its current area of occurrence, from 5,237,129 km^2 to 3,227,568 km^2 in 2050 and 2,486,240 km^2 in 2070. *Ontherus appendiculatus* is projected to lose 52.1% of its area of occurrence in the future, from 3,434,034 km^2 in the present to 2,081,253 km^2 and 1,648,320 km^2 in 2050 and 2070, respectively. *Trichillum externepunctatum* has the lowest projected loss in the area of occurrence, nevertheless, a reduction of 49.9% was estimated, from 3,602,200 km^2 in the present to 2,463,608 km^2 in 2050 and 1,805,550 km^2 in 2070.

4. Discussion

Our findings suggest a catastrophic future scenario for dung beetle species in Brazilian grasslands. The future spatial retraction within the Southeast of Brazil indicates that key dung beetle species will be restricted to areas with minimum priority for livestock intensification (Figures 3 and 4). *Dichotomius bos* and *D. nisus* are the species with the greatest reduction in suitable areas, the former with an impressive 70.7% loss of occurrence area. We believe that these species may be more prone to lose suitability due to their large size and longer reproductive cycle [54,55]. Moreover, *O. appendiculatus* and *T. externepunctatum* can be found during the entirety of the summer rains (October to March), while *D. bos* is collected mainly at the beginning of the rainy season and *D. nisus* is collected throughout but is more common at its end [56].

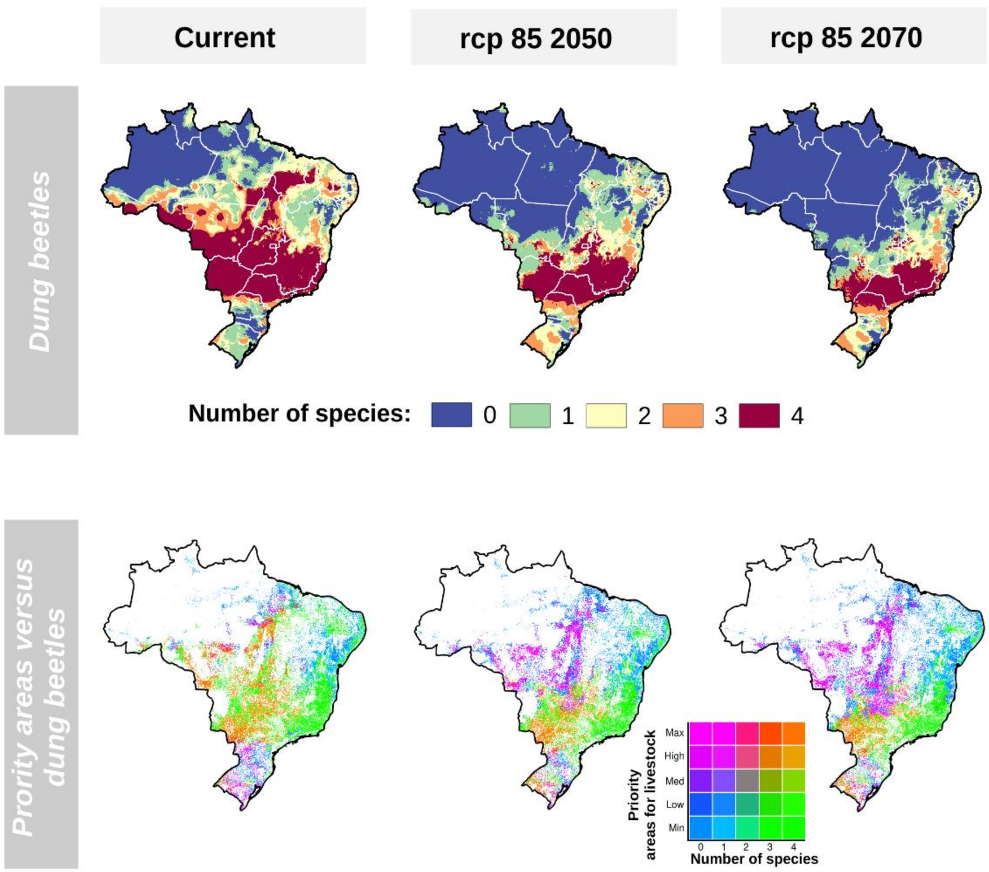

Figure 4. Dung beetle species presence based on present, 8.5 RCP 2050, and 2070 scenarios (upper panel) (See Figure S2). Priority areas for livestock intensification (*sensu* Barbosa et al., 2015) [48] and dung beetle species suitability for present, 8.5. RCP 2050 and 2070 scenarios (lower panel).

The species studied here are common in most South American grasslands (Figure 2) and are not usually found in forests. Our findings suggest that future suitable sites for the most common dung beetles would be in the Atlantic Forest region that is a non-priority region for livestock intensification (Figure 4). However, its highly endangered native vegetation is protected and controlled by law [57]. Therefore, while climatically suitable, this area has less suitable landscapes for grassland-related dung beetles.

The area occupied by livestock farming in Brazil includes almost 150 million hectares of pastures [58], mostly concentrated in biomes characterized by natural open areas as Pampa, Pantanal, Caatinga, and Cerrado and, more recently, in the Amazon [58]. The Amazon has been the biggest target of deforestation to create extensive pastures; Pará state has the second-largest grazing area in Brazil, with more than 20 million hectares of pastures [59]. In our projections, there is no future suitability for key native pastureland dung beetle species in the Amazon region (mainly Pará and Mato Grosso states), which is the area in Brazil that has the biggest pastures and herds [58].

There are more than 800 known native dung beetle species in Brazil [60], but the number of native species collected in Brazilian pastures has been smaller through the years [56]. The reduction in dung beetle species was observed in the state of Mato Grosso do Sul, Brazil, on a farm surveyed weekly for 26 years [61]. In the first years of sampling, the dung beetle community was composed of 40 native species, mainly tunnellers (dung beetles that bury feces from 10 to 120 cm below the dung pad) [60]. In the fourth year, *D. gazella*, a medium-sized tunneller, was introduced, and the dung beetle community changed drastically; native tunnellers became nearly extinct locally. A few years later, the population density of *D. gazella* started to decrease, but the species composition was not the same as before [61]. The number of native tunnellers was drastically reduced and, as a consequence, the amount of dung buried decreased significantly. This could have been avoided if native species were well studied prior to the introduction of *D. gazella* [61–63].

The burying activities of different dung beetle species delay the need for pasture restoration as they promote bioturbation from 0 to over 150 cm [64], which reduces soil compaction and improves permeability [16,18]. Again, without dung beetle activities, pastures will accumulate dung, limiting space for grass growth and increasing the need for more pesticides to control. With fewer species in pastures, fewer services will be provided. The suggestion of intensification in certain areas is relevant, particularly for pasture restoration and semi-intensive encouragement. Deforested areas that are not suitable for livestock intensification can be turned into reforestation regions or integrated crop-livestock-forest systems (ICLF). Besides other potential benefits for the herd and the environment, dung beetles occurring in silvopastoral systems are the same species that are common in pastures [65].

Dung beetles have been evolving and surviving different climate conditions since the megafauna extinction and Pleistocene climate oscillations; what dung beetles have not been supporting or surviving is the amount of chemicals present in livestock feces. Studies have shown that avermectins cause the death of dung beetle larvae or strong reductions in reproductive capabilities [66–75]. The consequences for this are pastures filled with dry and compacted dung pats that limit the space for cattle to forage [76], reduce overall pasture productivity [77], and increase the frequency of pasture restoration.

It is unsure how much recent climate change, deforestation, release, and subsequent spread of *Digitonthophagus gazella*, and intensive use of parasiticides and pesticides in Brazil have been responsible for the present observed reduction in native dung beetle diversity and abundance in pasturelands. Even *D. gazella*, presented as suitable climatically to occupy the southern and eastern Amazon regions [24], has been collected in those regions on few occasions and with fewer specimens; *Dichotomius bos*, *D. nisus*, *O. appendiculatus* and *T. externepunctatum* have not been found in the same areas or, when present, are mostly found dead near spotlights [65]. Our data suggest that climate change is part of the problem, but as avermectins have been used for 40 years, and the introduction of *D. gazella* over 30 ago also contributed to the decrease of native species in pastures observed over the last 20 years [56,61]. We suggest that new protocols for pesticides must be proposed and tested, especially in areas of semi-intensive livestock production.

5. Conclusions

Suitable areas for key dung beetle species are much smaller under future climate conditions. Key native dung beetle species are not likely to be present within the highest priority areas for livestock intensification in Brazil. This indicates the possible depletion of ecosystem services provided by these species in cattle farming regions. Climate change is the main cause for range reduction, but we also highlight the possibility of a stronger negative effect when global warming is correlated with the use of chemicals that are toxic to dung beetles. We suggest that studies on the use of anti-parasitics associated with rotation and/or silvopastoral systems be conducted, in order to achieve more effective and sustainable cattle production.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/agronomy11102033/s1, Figure S1: True skill statistic (TSS) values for niche-based modeling of *Dichotomius bos*, *Dichotomius nisus*, *Ontherus appendiculatus*, and *Trichillum externepunctatum*. Figure S2: Number of key dung beetle species on priority areas for livestock intensification (*sensu* Barbosa et al., 2015) in the present, 8.5 RCP 2050 and 2070 scenarios. Figure S3: Effects of future climate change across latitude and elevation for dung beetles. *** Indicate pairwise significance of $p < 0.001$ between scenarios.

Author Contributions: Conceptualization, M.E.M., T.S.-S. and F.Z.V.-d.-M.; methodology, all authors; software, M.E.M., T.S.-S. and V.M.P.; validation, M.E.M., F.Z.V.-d.-M. and T.S.-S.; formal analysis, M.E.M., V.M.P. and T.S.-S.; investigation, M.E.M. and F.Z.V.-d.-M.; resources, all authors; data curation, all authors; writing—original draft preparation, M.E.M.; writing—all authors; visualization, all authors; supervision, F.Z.V.-d.-M.; project administration, F.Z.V.-d.-M.; funding acquisition, F.Z.V.-d.-M. All authors have read and agreed to the published version of the manuscript.

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