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Climate change impacts the non-market value of nature: A case study of birding cultural ecosystem services in South Africa

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Abstract

Climate change and human activities are increasingly straining global ecosystems, threatening the essential benefits - ecosystem services - they provide to humanity. Among these, cultural ecosystem services (CES) enhance human well-being by providing non-material non-market value beyond what is accounted for within our market based economies. Measuring the impacts of global change on these benefits remains challenging and underdeveloped. In this study, we quantify the current and future non-market use value of birding CES across South Africa, a biodiversity hotspot, by integrating social sensing data, machine learning, and econometric methods. We reveal national patterns of birding CES use and non-market value, identify beneficiaries, and demonstrate that domestic and international beneficiaries are driven by distinct social-ecological dynamics, leading to differing CES vulnerabilities under future climate and biodiversity scenarios. While most protected areas are projected to experience declines in CES value, domestic birders show more resilience, with some gains in high-value CES regions, highlighting greater vulnerability for international CES non-market value and tourism. Our findings emphasize the need to incorporate non-market CES values into global change scenarios, offering a more holistic framework that integrates ecological stewardship and human well-being, while presenting novel approaches to overcome historical limitations in the field.

1. Introduction

Anthropogenic drivers, such as climate and land use change, are significantly altering the structure and functioning of ecosystems worldwide, impacting the benefits nature provides to people, as evidenced by an observed global decline in ecosystem services (ES) [1]. Ensuring the continued benefits of ecosystems amidst an unstable global climate is critical for supporting quality of life, safeguarding human well-being, and minimizing economic impacts [2]. This is particularly important in developing

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countries where dependence on ES and vulnerability to climate change is greater [1,2]. This focus is reflected in global initiatives, including the Sustainable Development Goals, the Post-2020 Global Biodiversity Framework, and the Paris Agreement, which emphasize the need to understand and address global change from a coupled social and ecological perspective to mitigate future impacts on both systems [1–3]. Despite these considerations, most assessments and policies tend to treat these issues and systems as distinct entities, addressing either ecological or social systems independently [2–4]. ES assessments have largely focused on ecological traits and processes resulting in ES (i.e., supply), without considering actual human use of ES [1,2]. This has led to a misunderstanding of benefits, as use is more directly linked to well-being and there are often mismatches between supply and use [2,5]. This oversight stems from limitations in data and methodology, resulting in knowledge gaps regarding the impacts of global change on ES and the subsequent impacts on people and society, especially in developing countries which tend to be less studied but have a greater reliance on nature [2,6].

These challenges are compounded by the fact that ES provide value beyond what is captured by conventional market-based economies, often offering crucial non-market benefits for human and societal well-being [7]. This is particularly evident with the often-overlooked non-material benefits nature provides, such as recreation, tourism, sense of place, and aesthetic appreciation—collectively known as cultural ecosystem services (CES) [8,9]. CES are highly nonlinear, subjective, and intangible, yet they contribute significantly, both directly and indirectly, to human well-being and economies [9,10]. CES emerge from people's interactions with and perceptions of nature, creating considerable value for individuals and society at large, especially in the form of non-market value [11]. Further, this connection between people and ecosystem structure and function leads to CES being the most perceived ES among individuals, presenting an opportunity to improve the social license for conservation and leading to synergies between human well-being and ecological health [12]. CES generates both direct economic value (e.g., visitation), indirect economic value (e.g., avoided health costs), and non-market value (e.g., recreation) [13]. Thus, as climate and other global change drivers affect ecosystems, impacts will compound through the market and non-market benefits ecosystems provide to people. To enhance mitigation and adaptation strategies, and reduce future economic and human impacts, it is essential to better understand the present and future dynamics of CES and derived CES values, including the often unaccounted for non-market values in understudied regions of the world [6]. Therefore, to comprehensively account for the value ecosystems provide to people, assessments need to look beyond just the biophysical supply and market values of ES and take a beneficiary perspective, accounting for the evolving nature of ES use and non-market values [6,14].

Social sensing datasets (i.e., collection of observations about people and the physical environment from humans and/or their devices [15]), like the eBird citizen science project [16,17], offer rich behavioral data on beneficiaries, enabling the assessment of CES use across broad spatiotemporal scales and in understudied regions [18]. However, these datasets are rarely used in ES models [19]. Machine learning allows us to handle large social sensing datasets more efficiently, providing a useful tool for assessing the non-linearity and subjectivity presented by CES [19,20]. Econometric methods, like the travel cost method, further allow for the estimation of the vast and often overlooked non-market use values provided by CES. Together, these tools represent a potential path forward for better mapping, modeling, and valuing the expansive non-material benefits and non-market values provided by nature.

Our approach for assessing the non-market use values of CES and the risks climate change poses to those values is demonstrated through a case study of birding in South Africa (Fig 1), a globally recognized biodiversity hotspot with a thriving recreation and ecotourism sector. This is especially the case for birding CES, as South Africa has remarkably rich avian diversity that attracts tens of thousands of local and international birders annually [21, 22]. Our study aims to extend beyond methodological contributions by illustrating the spatial impacts of climate change, and other drivers, on the non-market use value of birding CES across South Africa under future climate scenarios. This approach can provide insights for management, enabling organizations such as South African National Parks to identify and prioritize regions characterized by high current birding CES value and significant future vulnerability. By facilitating more informed management strategies, this approach can support South African conservation objectives of robust ES flows to people [23], while also providing a replicable framework for monitoring and assessment of diverse CES values.

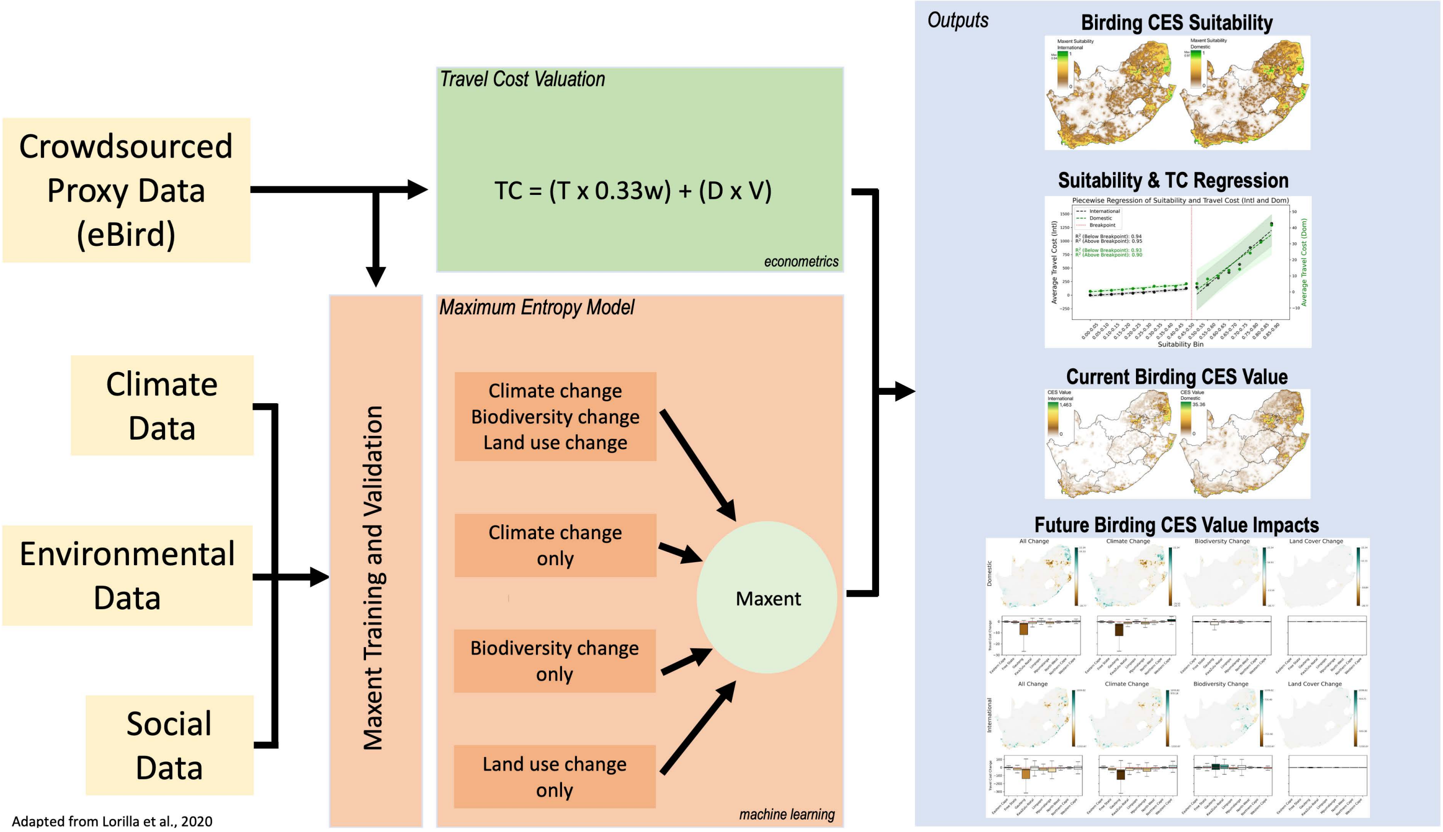

Fig 1. Conceptual framework of the key steps of the study. Administrative boundaries sourced from World Bank: https://datacatalog.worldbank.org/search/dataset/0038272/World-Bank-Official-Boundaries.

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2. Methods

2.1. Study area

South Africa's unique geography supports a remarkable ecology, containing 3 of the world's 36 biodiversity hotspots: the Succulent Karoo, the Cape Floristic Region, and Maputaland-Pondoland-Albany [24]. South Africa harbors 8% of global bird species (98 endemic species, 5 endemic breeding species, and 62 near-endemics) [25,26]. This rich avian diversity attracts many domestic and international birders, contributing to birding tourism being the second most popular biodiversity-based tourism activity in Africa, with South Africa playing a significant role [27]. Birding ecotourism is increasingly important for promoting sustainable economic and social growth, while simultaneously safeguarding ecosystems and the myriad services they provide across South Africa [27–30]. However, South African ecosystems, species, and the benefits they provide to people, face considerable threats from human-induced impacts, notably climate change [31].

2.2. Mapping birding CES: eBird data

Data from eBird, a citizen science platform, was collected for the period of 2010–2019 in South Africa from the Global Biodiversity Information Facility to map and model birding CES [32]. All data collection and processing complied with the eBird terms of service [33]. eBird allows birders to contribute to citizen science by uploading spatiotemporally geolocated points representing bird sightings, while also offering an application to interact with other birders and keep track of lifelong bird sightings, available globally since 2010 [16,17]. Our dataset contained a total of approximately 2.84 million unique geolocated eBird uploads in South Africa, which we used to gain insights on birders rather than eBird's typical use for insights on birds. We use each geolocated upload as an indication of a birder making use of birding CES. To minimize bias from users who upload many checklists in a single day, we use the common method of filtering for user-days, retaining only each unique user's first upload per day [34]. This refined the dataset to approximately 57,000 user-days, each represented by a geolocated point corresponding to the user's first list uploaded on a given day, indicating distinct birding visits to a specific area. Additionally, we exclude data points located within urban areas [35] to mitigate potential biases arising from highly populated urban environments, as recreational activities in these areas may not be influenced by environmental and climatic factors in the same way as in non-urban settings. Urban areas in South Africa were identified from the Africapolis database, which cross-references satellite and demographic data to identify agglomerations [36]. This resulted in a final dataset of 45,385 geolocated user-day points from 3,148 unique users, representing non-urban birding CES use throughout South Africa.

2.3. Modeling birding CES: Maxent

Maximum entropy modeling (Maxent) [37] was used to calculate the probability distribution for birding CES across South Africa (i.e., suitability). Maxent uses birding presence data as the response variable, integrating environmental and social predictors associated with each presence point. It also uses background points to comprehensively describe the spatial distribution of these predictors throughout the entire study area. With this, Maxent creates constraints based on features and the relationship between features and the response variable, optimizing the response variables' probability distribution by finding the most uniform distribution (i.e., maximizing entropy) while conforming to these constraints [38]. Maxent is particularly well-suited for our analysis, given that eBird data captures the presence of birding CES without corresponding absence data. This enables the prediction of current and future suitability of birding CES across South Africa while minimizing bias and incorporating uncertainty through a suitability score ranging from 0 to 1, with higher values indicating greater suitability. This approach is ideal for modeling CES given its inherent context-dependency and complexity, as it effectively communicates the uncertainties associated with quantifying an ES that is highly subjective. By providing suitability scores rather than precise predictions, Maxent offers a more appropriate and informative tool for decision-makers, enabling better interpretation of uncertainties in CES suitability.

The Presence-only Prediction Maxent tool in ArcGIS Pro was used to implement the Maxent algorithm. To identify relevant predictors, test hypotheses about CES flows (i.e., the flow of ES from landscape attributes to use by people), and optimize the model, we tested a total of 28 predictors hypothesized to impact both social and ecological aspects of birding CES (Table A in S1 Text). We used variable importance (calculated as the aggregate of absolute coefficients), model summary metrics such as AUC and omission rate, assessment of variable collinearity, and 3-fold cross-validation metrics to fine-tune model hyperparameters (basis functions and number of knots), determine the inclusion of variables, and optimize the final model. After testing 28 plausibly relevant variables, we included 12 predictors in the final model (Table A in S1 Text). Climate covariates include mean annual temperature, heat index, cloud cover, and wind speed. Biodiversity covariates include bird species richness and biodiversity intactness index. Environmental variables include Euclidean distance from closest protected area, Euclidean distance from water bodies, elevation, and land cover. Social covariates include accessibility (i.e., estimated travel time to closest major city) and gross domestic product. Details on the resolution and source of the data can be found in the supplement (Table A in S1 Text). All covariates were averaged for the period of 2010 to 2019. The statistical significance of the variables was tested using a fitted linear regression (Python sklearn), finding all variables in the final model significant ($p < 0.05$). We established the optimal presence probability cutoff for the models at 0.5 by computing the value at which the model's Youden's J statistic is highest, where both specificity (true negatives) and sensitivity (true positives) are maximized (Fig G in S1 Text). Using the tested covariates and users' identified home countries from the eBird data, we created separate Maxent models for domestic, international, and all birders. Future modeled climate, biodiversity, and land cover covariates are then used to model future suitability for domestic, international, and all birders under two future shared socioeconomic pathways: SSP245 and SSP585 (Table A in S1 Text). Further, to examine the marginal effects of various CES change drivers, we ran separate models for climate, biodiversity, and land cover change, incorporating future projections for each corresponding model while holding all other variables constant.

2.4. Valuing birding CES: Travel cost

Using geolocated eBird data and associated metadata, we estimate the broad non-market use value of birding CES through the travel cost method, a commonly used revealed preference ES valuation method [39–42]. Since CES are not traded in traditional markets, we use travel cost as a proxy for the non-market use value of CES by estimating the cost incurred by visitors (i.e., birders) to travel to their destination. The purpose of this valuation is not to provide a precise dollar amount of these non-material benefits, but rather to offer a general estimate of birding CES non-market use value across the country. The fundamental concept behind the travel cost method is that the expenses associated with the travel time and costs reflect the 'price' of accessing CES [43,44]. Therefore, beneficiaries' minimum willingness to pay for using a CES can be estimated from the frequency of visits at varying travel costs [45]. Traditional datasets used to estimate CES use and travel cost, including interviews, surveys, and focus groups, tend to be costly in terms of time and money, focus on smaller local scales or specific sites, and are limited in sample size [40,46]. The substantial increases in social sensing data globally offers extensive new insights into human-nature interactions, enabling us to overcome spatiotemporal constraints in assessing and valuing individuals' preferences and behaviors regarding CES.

We calculate travel cost as the cost of round-trip travel and the opportunity cost of time spent traveling [44]. Home location inferring methods are used to estimate the country of origin of each unique eBird user in the dataset [47]. By querying the entire eBird dataset, we estimate each users' home country as the country in which they upload the most throughout all time for users with at least 10 uploads (Table B in S1 Text). This "backyard birding" behavior is the most common among birders [48,49]. For international trips, we estimate trip length as the duration within which a unique eBird user uploads in South Africa within a 2-week. If an international user does not upload in South Africa within 2 weeks of their last upload, it is assumed the trip has ended with the length being from the first upload to the last upload. For domestic trips, we estimate trip length similarly, but with a timeframe of 1 day as many domestic birders take day trips

[49]. For international birders, we use each user's first upload within South Africa to determine the closest major airport (Cape Town, OR Tambo, and King Shaka). The Haversine formula is then applied, using the geopy package in Python, to calculate the distance between the population weighted centroid [50] of each user's home country and the closest international airport to their first upload. For domestic birders, we estimate the home province similarly to international birders, and calculate the shortest road distance from population weighted province centroids to each user's first upload using the Google Maps API through the googlemaps Python package.

Using the eBird data and the derived travel data, we apply the travel cost method to estimate a dollar value representing the non-market CES value of each birding trip. To estimate the cost of travel (CT) for international flights we multiply the distance traveled by the average cost per km traveled (Eq. 1). Cost estimations for travelers are based on calculations from Dudas et al [51]. We use their global air travel curvilinear cost per km traveled, which varies for short-haul (<2,000 km = 0.256 USD/km), medium-haul (2,001 – 4,000 km = 0.160 USD/km), long-haul (4,001 – 9,500 km = 0.140 USD/km), and ultralong-haul flights (>9,500 km = 0.122 USD/km) [51]. For domestic trips, CT is calculated using corresponding monthly South African petrol prices from 2010 to 2019 [52] and the average fuel consumption of light-duty vehicles in South Africa (0.074 litres/km) [53] (Eq. 2). Since global air travel cost per distance estimates are from 2010, we use the Consumer Price Index (CPI) to calculate the inflation rate (IR) (Eq. 3) and adjusted cost of travel (ACT) (Eq. 4) for inflation to each respective year and country being estimated within the data. Global CPI estimates for each country and each year within the study period (2010 – 2019) are acquired from the World Bank [54]. Monthly exchange rate data [55] from 2010 to 2019 is used to adjust values to USD, ensuring all values are comparable. Final reported values are adjusted to 2022 USD to provide a more current contextualization of the dollar amounts.

$$CT_{int} = D_{int} \times C_{d,int} \tag{1}$$

$$CT_{dom} = D_{dom} \times C_{d,dom} \times 0.074 \tag{2}$$

$$IR_j = \frac{CPI_{c,j} - CPI_{c,2010}}{CPI_{c,2010}} \tag{3}$$

$$ACT_j = \frac{CT_j}{1 + IR_j} \tag{4}$$

Where, CT_{int} is the cost for international trips ($), D_{int} is the international distance traveled (km), $C_{d,int}$ is the average cost per international distance traveled ($/km), CT_{dom} is the cost for domestic trips ($), D_{dom} is the domestic distance traveled (km), $C_{d,dom}$ is the average cost per domestic distance traveled ($/km). IR_j is the inflation rate in year j, $CPI_{c,j}$ is the Consumer Price Index for a given country c, in year j. ACT_j is the adjusted cost of travel in year j ($), and CT_j is the cost of travel in year j ($).

To estimate the opportunity cost (OC) of time, we use the customary method of calculating 1/3 of the hourly wage rate as the per hour cost of travel time (Eq. 5) [40,56,57]. For international visitors, we use annual adjusted net national income (NNI) per capita from the World Bank [54] for each corresponding birder's home country to estimate each birder's income. Income is then divided by 2000 to get the hourly wage rate (40 hours/week, 50 weeks/year). We then take 1/3 of the wage rate to calculate the hourly OC. To get the total OC per trip, we divide the round-trip distance traveled for each unique trip (km) by the average cruising speed of a commercial airplane: 926 km/hour (500 knots). For domestic travelers, we use the same method but use an average driving speed of 64 km/hour (40 miles/hour) (Eq. 6) [58].

$$OC_{int} = 0.33 \times \frac{NNI_{c,j}}{2000} \times \frac{D_{int}}{926} \tag{5}$$

$$OC_{dom} = 0.33 \times \frac{NNI_{dom,j}}{2000} \times \frac{D_{dom}}{64} \tag{6}$$

Where, OC_{int} is the opportunity cost of time for international visitors ($), $NNI_{c,j}$ is the annual adjusted net national income in country c, and year j. OC_{dom} is the opportunity cost of time for domestic visitors ($), $NNI_{dom,j}$ is the annual adjusted net national income in South Africa, and year j.

To calculate the final travel cost (TC) in $ for each unique trip, we take the sum of the adjusted cost of travel (ACT) and the opportunity cost of time (OC) (Eq. 7).

$$TC = ACT + OC \tag{7}$$

2.5. Modeling CES value: Maxent and travel cost

After calculating travel costs for each geolocated trip in the eBird dataset, we modeled CES value across the entire landscape. By overlaying the modeled birding CES suitability and geolocated travel costs, domestic and international travel costs were spatially sampled within each Maxent suitability raster pixel. Using piecewise regression with a 0.5 suitability breakpoint, we established the relationship between suitability and average travel costs for domestic and international birding CES. This approach enabled the calculation of CES value per pixel across the country, even where we did not have eBird data, linking the social-ecological drivers of CES use to CES value. For future scenarios, we applied the piecewise regressions to future birding CES suitability rasters, allowing us to model future CES value and changes. These were represented as the average CES value of pixels across South Africa (Fig 1 for a conceptual figure of the methods). Thus, results pertaining to CES value and changes in CES value refer to these modeled values, while references to travel cost pertain to the calculated travel costs from our eBird dataset.

3. Results

3.1. Birding CES

Birding CES use is widespread throughout South Africa, with notable concentrations observed in the northeast, particularly in and around Kruger National Park, and in the southwest, predominantly within the Cape Floral Region Protected Areas (Fig 2c). Our eBird proxy also reveals seasonal visitation patterns with most visits occurring in late spring and early summer (Fig 2d). Although birding CES likely increased year over year from 2010 to 2019, like other tourism in South Africa [59], the annual growth seen in our data is also likely due to the increasing use of eBird. Domestic birders constitute the second highest group of birders after visitors from the United States (Fig 2b). International birders traveling to South Africa to take advantage of the unique and diverse CES in the region mainly come from the United States, Canada, Australia, the United Kingdom, and India (Table B in S1 Text). The most highly visited South African provinces (Western Cape, Mpumalanga, KwaZulu-Natal, and Limpopo), have the majority of birding visitation from international birders (Fig 2a). Of all nine provinces, only Gauteng and Eastern Cape have most birding coming from domestic birders. Most non-urban birding CES across the country is within protected areas (89%), particularly Kruger National Park, Cape Floral Region Protected Areas, and iSimangaliso Wetland Park (Fig 2c).

3.2. Travel cost and suitability

From 2010 to 2019, international birders accounted for 3,976 trips (~27% of all trips) in our dataset, with an average trip duration of 37 days (Table 1). These birdwatchers traveled an average distance of 12,028 km one-way to reach South Africa, incurring an average inflation-adjusted round-trip flight cost of $3,677 USD (± $1,004). Domestic birders accounted for 10,537 trips (~73% of all trips) within the same period, with an average trip duration of 2.7 days. Domestic

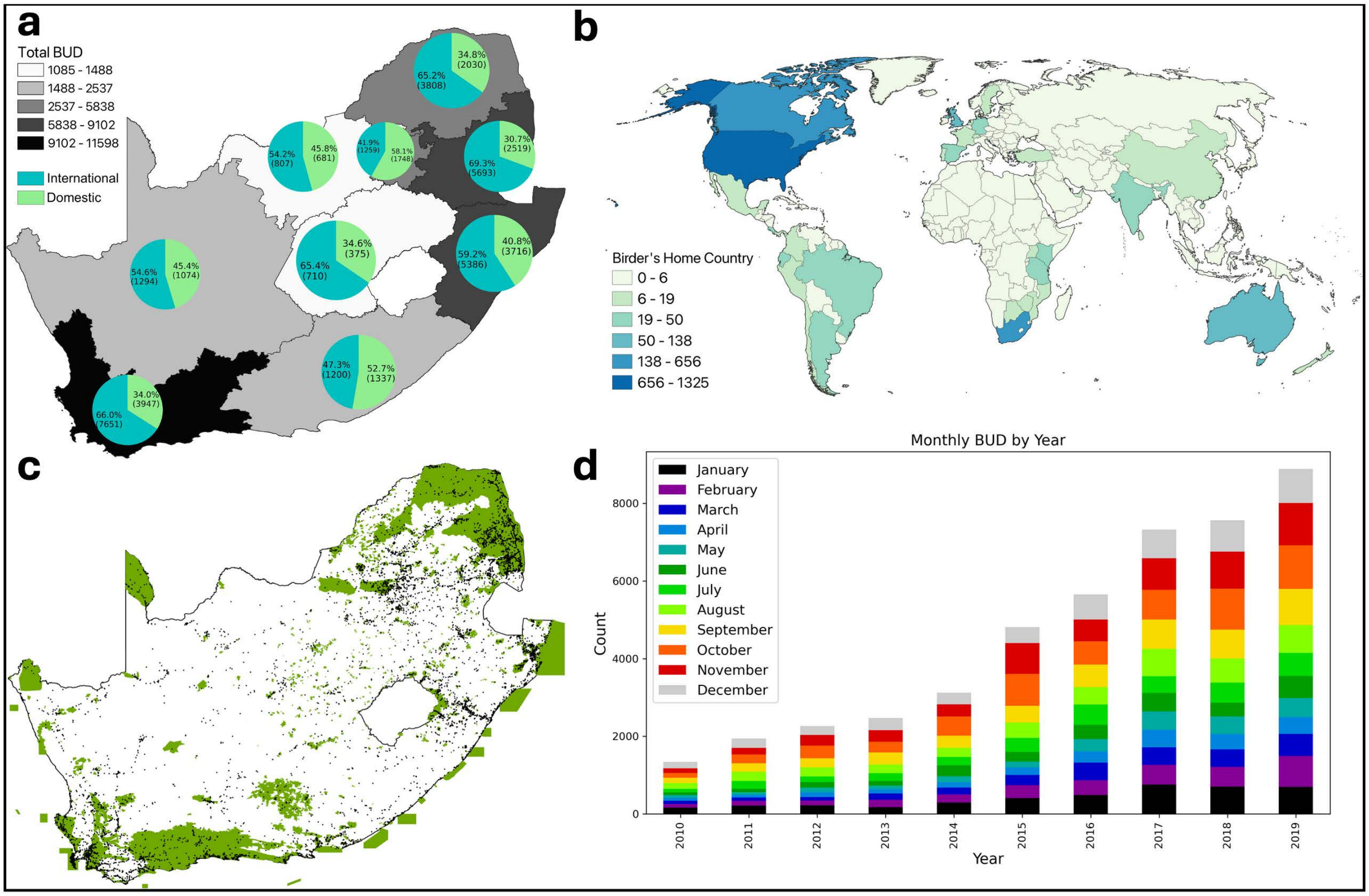

Fig 2. Birder Characteristics. a) Total BUD per province and proportion from international and domestic birders, b) home country of eBird visitors to South Africa, c) BUD pointws throughout the country with protected areas in green and, d) eBird upload patterns by month and year. Administrative boundaries sourced from World Bank: https://datacatalog.worldbank.org/search/dataset/0038272/World-Bank-Official-Boundaries.

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birders traveled an average distance of 410 km, resulting in an average inflation-adjusted round-trip driving cost of $58 (± $69, with costs remaining above $0). The opportunity cost of travel time averaged $173 (± $100) per trip for international birders and $12 (± $13, with costs remaining above $0) for domestic birders. The total mean travel cost per trip for international birders was $3,851 (± $1,069) and $70 (± $81, with costs remaining above $0) per trip for domestic birders. The overall total travel cost across South Africa was $14,748,561 for international birders and $734,542 for domestic birders. International birders' total travel costs per province were highest in the Western Cape ($5,061,366), Mpumalanga ($2,490,881), and Limpopo ($2,036,509), with the mean travel cost being highest in Limpopo ($3,954), Gauteng ($3,935), and the Western Cape ($3,846). For domestic birders, the total travel costs per province were highest in the Western Cape ($205,307), KwaZulu-Natal ($137,862), and Limpopo ($87,695), with the mean travel cost being highest in the Northern Cape ($127), Limpopo ($85), and the Free State ($79).

Our Maxent model for all birders resulted in an area under the curve (AUC) of 0.92, an omission rate of 0.19, and correct classification rate of 82%, 79%, and 81% across each validation fold. The domestic model resulted in an AUC of 0.92, an omission rate of 0.23, and correct classification rate of 77%, 76%, and 76% across each validation fold. The

Table 1. Descriptive statistics and description for variables derived from the eBird dataset, monetary values are in 2022 USD and distances are in km.

Variable	Description	Mean	Std. Dev.	Total
Country of origin	Country in which each unique eBird user has the most uploads (minimum 10 uploads)	–	–	–
International Distance	Distance (km) from population weighted origin country centroid to international airport closest to user's first upload	12,028	3,397	46,114,150
Domestic Distance	Road distance (km) from population weighted origin province centroid to first upload	410	438	4,287,145
International Trip Duration	Length of trip (days) (n = 3,976) for international birders	37	60	740,870
Domestic Trip Duration	Length of trip (days) (n = 10,537) for domestic birders	2.7	5.1	47,232
International Trip Flight Cost ($)	Round trip cost from user's home country to closest international airport to user's first upload	3,677	1,004	14,085,500
Domestic Trip Driving Cost ($)	Round trip cost from user's home province to user's first upload	58	69	611,112
InternationalOpportunity Cost of Time ($)	Round trip opportunity cost of the time spent flying from the user's home country to the closest international airport to the user's first upload	173	100	663,061
Domestic Opportunity Cost of Time ($)	Round trip opportunity cost of the time spent driving from the user's home province to the user's first upload	12	13	123,430
International Travel Cost ($)	Final international travel cost estimate accounting for cost of travel and opportunity cost of time	3,851	1,069	14,748,561
Domestic Travel Cost ($)	Final domestic travel cost estimate accounting for cost of travel and opportunity cost of time	70	81	734,542

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international model also resulted in an AUC of 0.92, an omission rate of 0.21, and correct classification rates of 79%, 78%, and 78% across each validation fold. Overall, suitability patterns and modeled CES value were relatively similar across all birders, with high suitability and value observed primarily in coastal South Africa (especially in the Cape Floral Region), the northeast in and around Kruger National Park, in eastern Mpumalanga, and the province of Gauteng (Fig 3 and Fig A in S1 Text). Some regional differences between domestic and international birders are prevalent though. Similarly, calculated travel cost patterns are related among all birders, with some regional differences between domestic and international birders (Fig A and Table C in S1 Text).

Our piecewise linear regression between suitability and travel costs, shows strong correlations for both international and domestic models. Specifically, the regression model for international birding CES suitability and travel cost resulted in an R^2 of 0.94 below the breakpoint and 0.95 above it (Fig 3). Similarly, the regression model for domestic birding CES suitability and travel cost exhibited a high correlation, with an R^2 of 0.93 below the breakpoint and 0.90 above it. Below the breakpoint, there is a slow linear increase in travel cost as suitability increases. Specifically, our estimates suggest that for every 0.05 increase in CES suitability below the breakpoint, on average international birders experience an increase of approximately $13.40 in travel cost and domestic birders see a $0.50 increase. Above the breakpoint for every 0.05 increase in suitability, international birders experience an increase of approximately $168.50 in travel cost and domestic birders see a $4.93 increase.

Calculating the disparity between the international and domestic modeled suitability reveals the variability in birding CES depending on the origin of the beneficiaries. Domestic birding CES tends to have higher suitability (shown by darker blue in Fig 4) in coastal South Africa, as well as near the major cities, such as Pretoria, Johannesburg, and Cape Town. In contrast, international birding CES tends to have higher suitability (shown by darker brown in Fig 4) in southwest South Africa, particularly in and around the Cape Floristic Region and the Succulent Karoo (biodiversity hotspots) as well as in northeast South Africa, particularly in and around Kruger National Park.

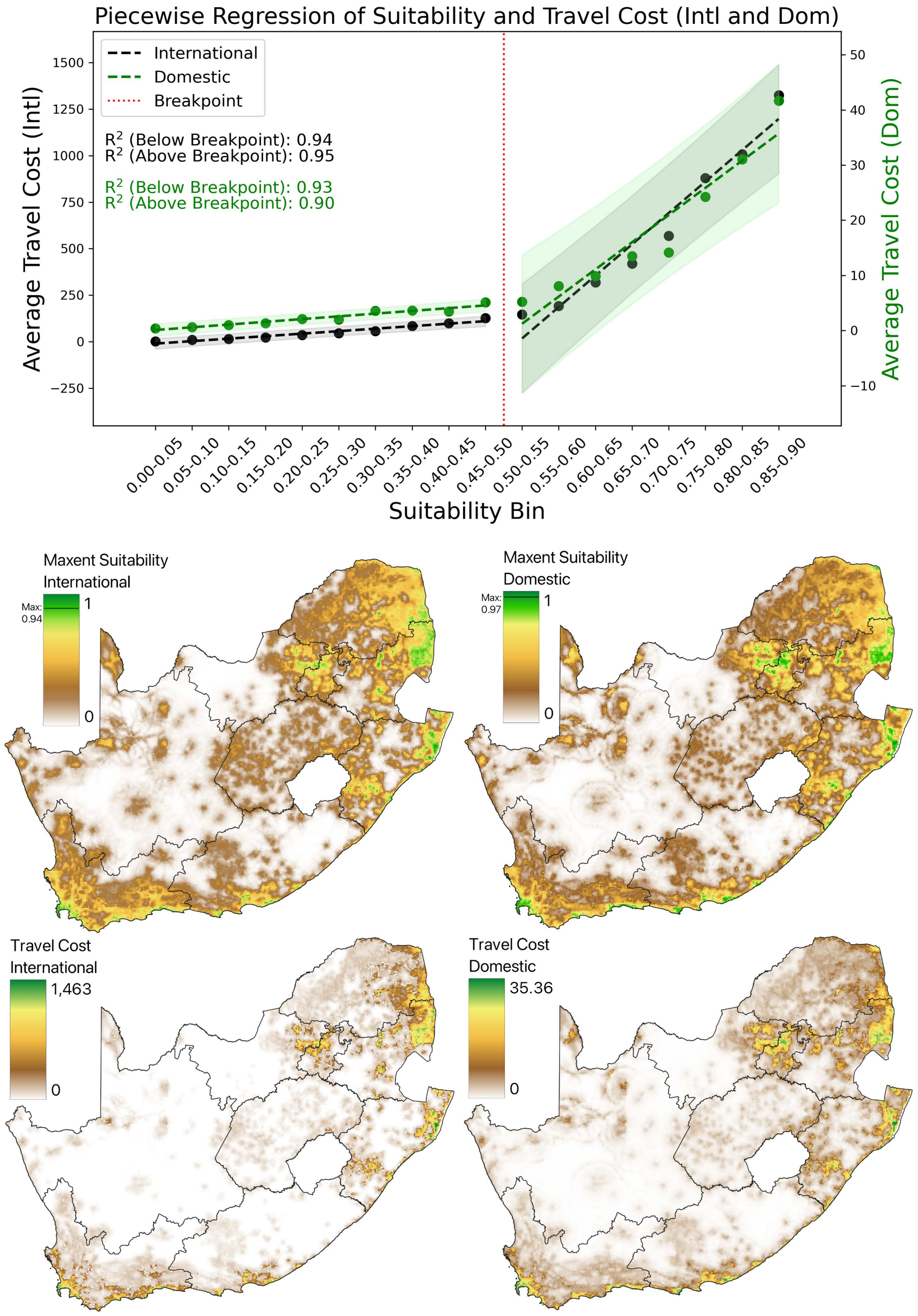

Fig 3. Piecewise regressions of average travel costs for domestic and international birding CES against 0.05 suitability bins from international and domestic Maxent models (top). Maxent suitability and modeled birding CES value maps for international and domestic birding (bottom). Administrative boundaries sourced from World Bank: https://datacatalog.worldbank.org/search/dataset/0038272/World-Bank-Official-Boundaries.

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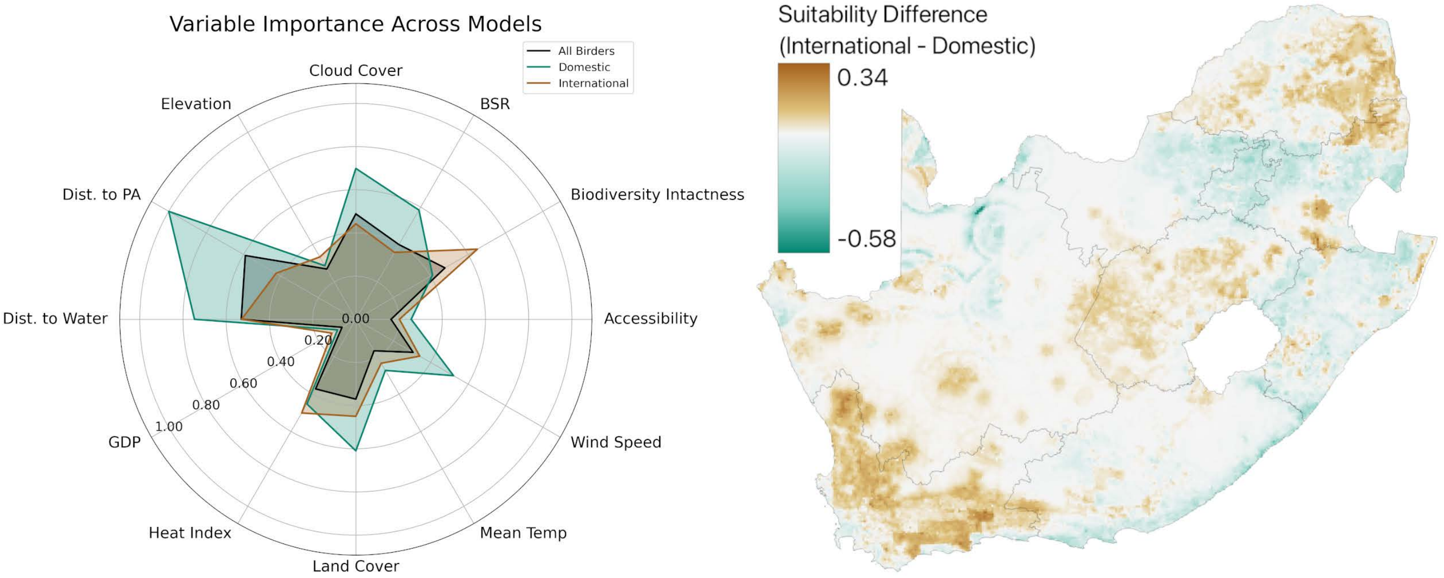

Fig 4. Normalized variable importance for domestic, international, and all birders (left). Difference in suitability between the international and domestic models with darker blue showing greater suitability for domestic CES and darker brown for international (right). Administrative boundaries sourced from World Bank: https://datacatalog.worldbank.org/search/dataset/0038272/World-Bank-Official-Boundaries.

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Variable importance calculations (aggregated absolute coefficients) highlight the differences in social-ecological drivers of birding CES (Fig 4). The associated partial dependence plots demonstrate the marginal impact of each driver on CES use (Fig B in S1 Text). Proximity to protected areas is a significantly more important driver for domestic birding CES compared to international, although it remains important for both. Other factors influencing domestic birding CES include proximity to waterbodies, bird species richness, land cover, and cloud cover. On the other hand, the primary drivers for international birding CES are biodiversity, proximity to waterbodies, land cover, heat index, and cloud cover.

3.3 Future impacts to CES value

Modeled impacts to future average CES values across all of South Africa show a total average decline of -\$0.65/km^2 (aggregated across the country = \$796,620 total average decline) a 21% decrease for international CES value and -\$0.02/km^2 (aggregated = \$26,902 total average decline), an 18% decrease for domestic CES value. Most declines in average CES value are projected to occur in and around Gauteng, within the Cape Floral Region in the Western Cape, and in KwaZulu-Natal (Fig 5). While decreases are more prevalent and of higher magnitude, especially in protected areas, several regions also show an increase in average CES value, with impacts accentuated with greater warming scenarios (see Fig C in S1 Text for SSP245 scenario results). For instance, parts of northeast South Africa and the coastal regions of KwaZulu-Natal and the Eastern Cape show increases in value. Model results reveal differences between domestic and international CES impacts (Fig 5). Domestic birders experience greater negative impacts in and around Gauteng, near two of the major cities, Johannesburg and Pretoria, while showing greater increases in northeastern South Africa, particularly in and around Kruger National Park. In contrast, international birders see more negative impacts in northeastern South Africa, including within Kruger National Park, which is currently the protected area with the highest total birding CES value. Overall, CES value is negatively impacted within most National Parks and World Heritage Sites in the future. Among the nearly 7,000 Nature Reserves, there is a more mixed impact, but the majority of reserves experience decreases in value.

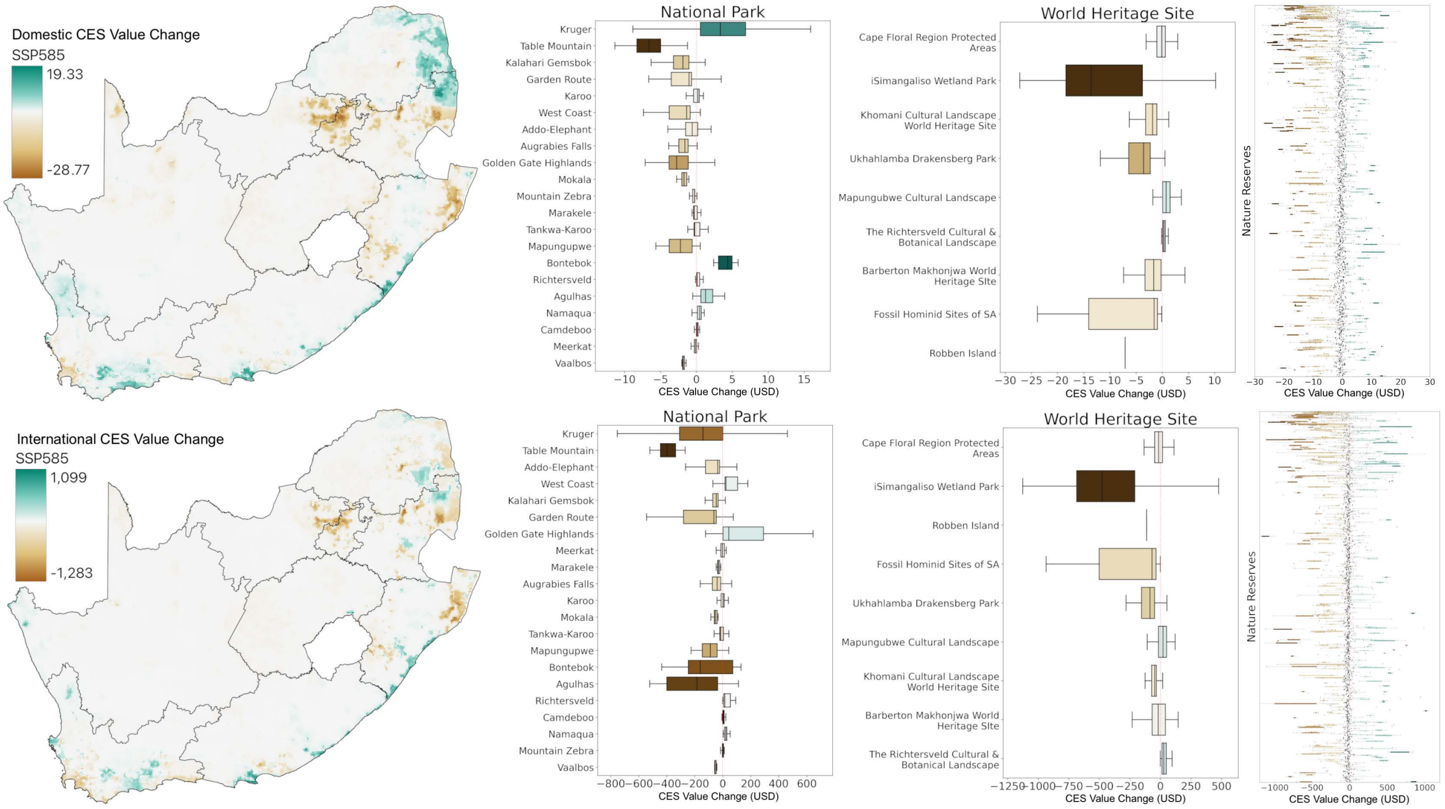

Fig 5. CES value change maps (SSP585) for domestic and international models (left). Box plots show domestic (top row) and international (bottom row) value change across national parks, world heritage sites, and Nature Reserves (all sorted from highest to lowest current value). Administrative boundaries sourced from World Bank: https://datacatalog.worldbank.org/search/dataset/0038272/World-Bank-Official-Boundaries.

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Different drivers of change to CES (i.e., climate change, biodiversity change, and land cover change) impact value differently across South Africa. Assessing the marginal impact of these drivers reveals that climate changes drives the most significant changes in future CES value across the country (Fig 6). Climate change driven decreases are observed across most of Gauteng, in regions of Mpumalanga, in northeast KwaZulu-Natal in and around iSimangaliso Wetland Park, and parts of the Cape Floristic Region biodiversity hotspot (mainly around Cape Point) (Fig 6). However, climate change also contributes to increases in average value in northeast South Africa in and around Kruger to Canyons, coastal Eastern Cape, and regions within the Succulent Karoo. The biodiversity change model shows a more balanced response between increases and decreases in value across the landscape, with greater impact on international birding CES. Biodiversity change contributes to both decreases and increases in CES value across parts of Gauteng, KwaZulu-Natal, and in and around Kruger National Park, with impacts accentuated for international birders. The land cover change model indicates minimal impacts across South Africa, with slight positive impacts in the northeast and negative impacts in the southwest.

4. Discussion

4.1 CES value flows: Domestic vs. international

We quantified CES flows using social sensing data and travel-cost analyses to estimate domestic and international non-market values, demonstrating that CES benefits extend beyond the local and indigenous communities who steward them, to global communities [60] (Fig D in S1 Text). Domestic birders (~21% of birders) predominantly engage in short,

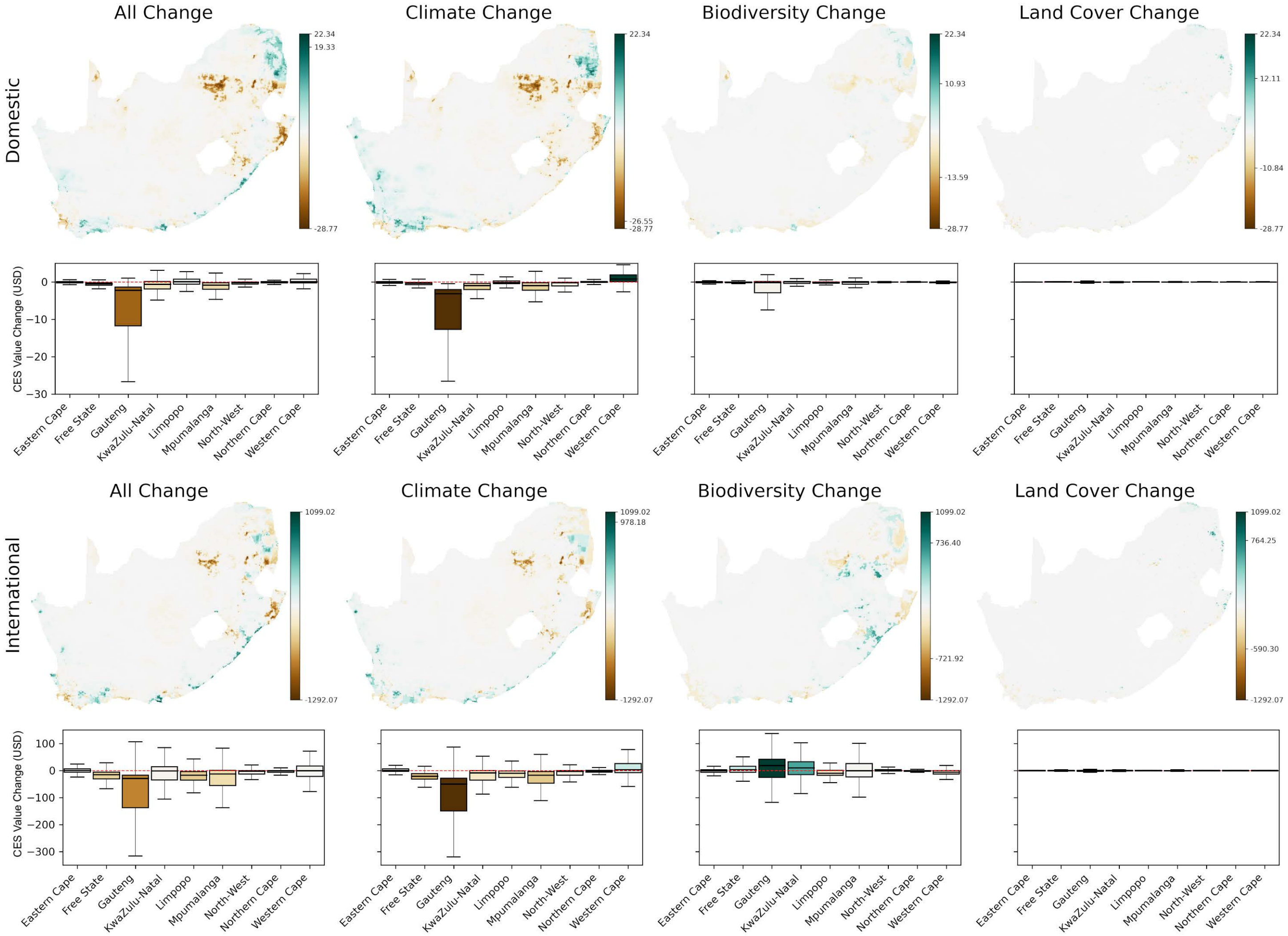

Fig 6. CES value change (SSP585) for domestic (top panel) and international models (bottom panel) for all four models showing the impact of different drivers of CES change. Boxplots show CES value change for each corresponding model within the 9 provinces of South Africa. Administrative boundaries sourced from World Bank: https://datacatalog.worldbank.org/search/dataset/0038272/World-Bank-Official-Boundaries.

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frequent trips, making up ~73% of all birdwatching excursions, but only ~6% of total birding days with an average travel cost of $12 per trip (total = $734,542 within our sample). Conversely, international birders, though embarking on fewer trips, opt for longer durations and much higher travel costs (averaging $3,851 per trip and totaling $14,748,561), reflecting greater time and resource investments by international birding tourists, who tend to be older and wealthier than the general population [61]. Further, this represents the significant value they receive in return via CES [62]. These contrasting patterns illuminate the contextually diverse motivations and value derived from CES that ultimately contribute to regional development benefits through increased visitation, local economic stimulation, job creation, financing for conservation and community-based initiatives, and beyond economics, through the promotion of cultural heritage and exchange, development of relational values, and increased environmental awareness. This underscores CES's multifaceted non-market contributions to sustainable, resilient social-ecological well-being [63–65] that must be integrated into land management and decisionmaking, particularly as disparities often exist between who benefits and who pays when conservation and management decisions are made [66,67].

Although international birders generate most market value and have higher travel costs, domestic beneficiaries derive substantial but distinct benefits, requiring separate valuation and consideration in conservation decisions. For example, drivers of CES differ across landscapes and between beneficiaries. Although protected areas are important overall for driving CES value, especially National Parks, World Heritage Areas, and Nature Reserves (Fig E in S1 Text), they are significantly more important for domestic beneficiaries, whereas international CES is more driven by biodiversity intactness (Fig 4). Suggesting that locals may garner more value from emotional or cultural connections to their local protected areas, whereas international tourists might derive more value from regions known for their ecological vitality. This dichotomy highlights the importance of place attachment and ecological health in shaping CES values and emphasizes the need for nuanced conservation strategies that account for the diverse social-ecological drivers of CES value, ensuring both conservation goals and beneficiary needs are met, particularly where synergies exist [68,69].

4.2. Social-ecological drivers of CES and climate change vulnerability

Climate conditions, significantly affect the flow and value of birding CES across South Africa. Heat index in particular plays a crucial role in shaping the flow of CES value to international beneficiaries (Fig 4 and Fig A in S1 Text), highlighting the susceptibility of CES, and specifically international tourism, to the impacts of a warming climate. This vulnerability is confirmed through our models which demonstrate that climate change will have the greatest marginal impact on future CES value over biodiversity and land cover change across all provinces of Sousth Africa and under both future scenarios (Fig 6 and Fig C in S1 Text). Impacts across protected areas are variable, but tend to be more negative, especially for international birders who, for example, see significant decreases in CES value in Kruger National Park (the protected area with the highest current total CES value), whereas domestic birders see a positive impact (Fig 5). Further, the province of Gauteng (location of two major cities Pretoria and Johannesburg) shows significant decreases in average CES value across all beneficiaries mainly due to changes in climate. Significant future impacts on average CES value underscores the influence that global change, especially climate change, can have on people's interactions with nature and subsequently, on sustainable economic development, especially in economies more dependent on ecotourism like many across Africa [70]. Although climate change is the main driver of impacts, biodiversity change shows a relatively greater effect on international birders compared to domestic birders (Table A in S1 Text). This is likely due to international birders' preference for regions with high biodiversity intactness, such as the Cape Floral and Succulent Karoo biodiversity hotspots and in and around Kruger National Park [71]. This illustrates the importance of extending global change scenarios and linking drivers to flows for better incorporation of CES and non-market values in decision making, [72–74].

4.3. Methodological innovation, limitations, and future directions

The rapid development and expansion of social sensing datasets enable detailed spatiotemporal analyses of CES beneficiaries, allowing for the modeling and valuation of non-market ES benefits at previously inaccessible scales and regions, enhancing the integration of social dimensions into ES valuation, at scales necessary for addressing the large-scale global social-ecological crises we face [18,75]. However, challenges remain, including the representativeness of social sensing data for the population of interest and spatiotemporal biases [76]. Social sensing data from eBird likely represents spatial patterns of birding well [77], but only represents a small portion of the total birder population (those uploading to eBird) and varies in demographic representativeness characteristics depending on the context [76]. For example, comparing 2010 data from our eBird sample with a 2010 survey of South African avitourism [78] shows matching patterns in domestic avitourist home provinces (top 3: Gauteng, Western Cape, and KwaZulu-Natal), good representation of proportional domestic versus international visitation, but overrepresentation of international visitation from the USA and underrepresentation of European birders (Fig F in S1 Text). Thus, future work should attempt to use sample selection bias correction where up-to-date survey data is available prior to modeling CES [76].

Machine learning algorithms, as demonstrated, provide a pathway to handle large datasets offered by social sensing and to bridge theoretical gaps in CES studies by offering a data-driven framework capable of addressing the complex, non-linear nature of human-environment interactions [18,79]. For example, we highlight significant correlations between the complex interplay of interacting social and ecological factors that produce birding CES and the value derived from these services. This exemplifies the specific interactions of landscape attributes that directly contribute to CES flows and value, where theory is otherwise difficult to develop due to the context dependency of CES. Despite its advantages, machine learning has drawbacks, caution and intentionality is needed when implementing these algorithms [19]. The data-driven nature can encourage the inclusion of numerous data layers to seek correlations, often overlooking the underlying causal pathways within the model. Causal relationships should be thoughtfully considered before testing with machine learning models, and efforts should be made to address the 'black box' nature of these algorithms. This can be achieved through diagnostics such as variable importance measures and response curves, which provide insights into model behavior and the hypothesized underlying relationships (Fig 4 and Fig B in S1 Text).

Finally, econometric methods allow for the quantification of the often-overlooked and difficult to quantify non-market use values of CES. Such valuation techniques should be approached with nuance, acknowledging that they are inherently imperfect and imprecise attempts to quantify something that is fundamentally subjective. Rather, they offer an interpretable representation of the diverse values that nature provides, extending beyond what is captured by market-based economies. For instance, a limitation of our application of the travel cost method is the assumption that all birders in the dataset were traveling solely for birding, which may not always hold true. However, evidence suggests that the vast majority of eBird data and users come from highly specialized birders who frequently travel primarily or exclusively for birding [49,80], a common characteristic of birding-related citizen science platforms [81,82]. For instance, one study found that 93% of eBird data within their sample was contributed by such specialized birders [80]. By combining this understanding of eBird user specialization with a minimum upload threshold, we assume that our sample reflects birders traveling specifically for birding. Nonetheless, future studies could further validate this assumption through targeted surveys and better address the multi-purpose trip issue through common methods like site-choice models [83]. Another limitation of using travel cost is that it undervalues the full non-market value of birding CES, as it does not explicitly account for non-use values, such as intrinsic and relational values [83,84]. Future studies could address this limitation by incorporating mixed-method approaches that combine economic metrics with qualitative assessments of cultural and relational values. These values, along with the non-market use value we measure, are crucial for capturing the broader significance of nature beyond immediate economic or utilitarian benefits [69,84].

Our approach advances the understanding of CES dynamics by integrating non-material and non-market impacts often overlooked or treated as externalities, although confined to the case of birding in South Africa. By combining social sensing data, machine learning, and econometric methods, we demonstrate how to assess the spatial and temporal patterns of CES use and the significant non-market value they provide. This approach highlights the unnacounted for impacts of global change on non-market values provided by CES and emphasizes the importance of equitable and nuanced conservation strategies that account for both domestic and international beneficiaries and needs. Future research can build on these tools to provide decision-makers and managers with a more holistic understanding of CES, including their intrinsic, relational, and other non-use values, and assess CES beyond birding, potentially using other social sensing datasets. By incorporating these often-neglected dimensions, we can better safeguard the environment's contributions to human well-being, address disparities in who benefits from CES, and prepare for the challenges posed by a rapidly changing world. Ultimately, this work underscores the critical role of CES in fostering resilient social-ecological systems and provides a replicable framework for valuing and managing these essential benefits provided by nature in the face of global change.

Supporting information

S1 Text. Supplement for: Climate Change Impacts the Value of Cultural Ecosystem Services: A Case Study from South Africa.
(DOCX)

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Writing – review & editing: Kyle Manley, Lacour Mody Ayompe, Benis N. Egoh.

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