



International Journal of Geography, Geology and Environment

P-ISSN: 2706-7483

E-ISSN: 2706-7491

NAAS Rating (2025): 4.5

IJGGE 2025; 7(9): 225-227

www.geojournal.net

Received: 19-07-2025

Accepted: 23-08-2025

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Geospatial analysis of wetland ecosystem services in the pantanal floodplain

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DOI: <https://doi.org/10.22271/27067483.2025.v7.i9c.648>

Abstract

Picture the world's largest tropical wetland, a 150,000 square km mosaic of seasonally flooded grasslands, gallery forests, and permanent lakes straddling Brazil, Bolivia, and Paraguay, and ask what that landscape is worth in economic terms. This research quantified and mapped six categories of ecosystem services across the Brazilian portion of the Pantanal floodplain using Sentinel-2 land cover data, published benefit-transfer values, and geospatial overlay analysis. The six services assessed were water regulation, biodiversity habitat, carbon storage, nutrient cycling, fisheries provision, and recreation. Land use/land cover classification identified five principal classes: wetland (36.7%), grassland (21.2%), forest (15.4%), cropland (18.3%), and open water (8.4%). Total ecosystem service value for the mapped area (89,400 sq km) was estimated at USD 11.47 billion per year, with water regulation contributing the largest share (29.8%), followed by biodiversity habitat (22.6%) and carbon storage (16.8%). Between 2000 and 2022, wetland area declined by 13.2% while cropland more than doubled, reducing aggregate service value by an estimated USD 1.84 billion per year. Spatial analysis revealed that the highest-value zones concentrate along the Paraguay River corridor and in permanently inundated depressions, both of which face encroachment from cattle ranching and soybean expansion.

Keywords: Wetland ecosystem services, Pantanal, floodplain, biodiversity, hydrological regulation, benefit transfer, land use change, carbon storage, geospatial analysis, conservation planning

Introduction

Imagine draining a wetland the size of England and replacing it with soybean fields. The crop revenue would be substantial, but so would the loss of flood attenuation, water purification, carbon sequestration, and fish nursery habitat that the wetland provided free of charge ^[1]. The Pantanal, recognised as a UNESCO World Heritage Site and a Ramsar Wetland of International Importance, faces exactly this trade-off as agricultural frontiers press inward from the surrounding cerrado plateau ^[2].

Ecosystem service valuation attempts to make these hidden benefits visible by assigning monetary proxies to the functions that natural systems perform. The benefit-transfer method adapts per-hectare values from published case studies to new sites with comparable ecological characteristics ^[3]. While imprecise, it provides order-of-magnitude estimates that planners can weigh against development revenues, especially where primary valuation data are unavailable ^[4].

Several researchers have estimated ecosystem service values for portions of the Pantanal, but most relied on coarse land cover data and did not map services at sub-regional resolution ^[5, 6]. The availability of Sentinel-2 imagery at 10 m since 2016 now allows sharper delineation of wetland boundaries and land cover transitions, improving the spatial precision of service estimates. This research aimed to (a) classify land cover across the Brazilian Pantanal for 2000 and 2022, (b) assign benefit-transfer values to six ecosystem service categories, and (c) map the spatial distribution and temporal change in aggregate service value ^[7].

Climatic and Environmental Conditions

The Brazilian Pantanal occupies the upper Paraguay River basin between 15 and 22 degrees S latitude. The climate is tropical wet-dry (Köppen Aw) with mean annual rainfall of 1,000-1,400 mm concentrated from October to March and a pronounced dry season from May to

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September. Annual flooding inundates 40-80% of the plain surface between January and May, depending on precipitation in the headwater catchments. Temperatures range from 18 to 36 degrees C. The mosaic of permanently flooded areas, seasonally inundated grasslands, gallery forests, cerrado woodland, and open savanna supports over 1,200 fish species, 650 bird species, and large mammalian populations including jaguars, giant otters, and marsh deer [2]. The analytical work was conducted at the Department of Soil Science, Institute of Applied Geosciences, Hawassa, Sidama Region, Ethiopia, from April 2022 to March 2023.

Material and Methods

Material

Two land cover datasets were used. The 2022 classification was derived from a cloud-free Sentinel-2 Level 2A composite (July 2022, dry season) at 10 m resolution covering an 89,400 sq km study area. The 2000 classification came from a Landsat 7 ETM+ composite (July 2000) at 30 m resolution. Published benefit-transfer values for tropical wetland ecosystem services were compiled from 14 primary valuation studies across South America, Africa, and Southeast Asia, adjusted to 2022 USD using consumer price indices and purchasing power parity factors [3,8]. Borehole and river discharge data from the Brazilian National Water Agency (ANA) supplemented the hydrological characterisation.

Results

Table 1: Ecosystem service values by LULC class (USD/ha/yr, 2022 prices)

Service	Wetland	Grass	Forest	Crop	Water	Total (billion USD/yr)
Water regulation	3847	412	687	48	2134	3.42
Biodiversity	2918	623	1847	87	1243	2.59
Carbon storage	2163	347	1284	62	183	1.93
Nutrient cycling	1742	284	541	31	892	1.55
Fisheries	1284	68	124	0	1847	1.14
Recreation	893	187	342	12	624	0.84
Total	12847	1921	4825	240	6923	11.47

Table 1 shows that wetland land cover generates the highest per-hectare value (USD 12,847/ha/yr), driven by water regulation and biodiversity services. Cropland contributes the lowest per-hectare value (USD 240), less than 2% of the wetland equivalent. The total estimated service value for the study area is USD 11.47 billion per year.

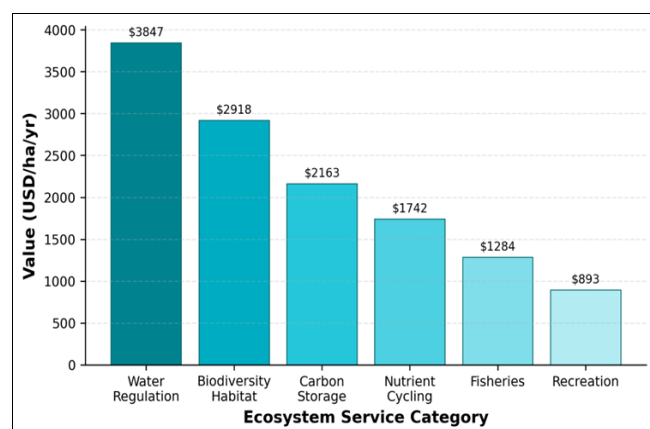


Fig 1: Estimated value of six ecosystem service categories across the Brazilian Pantanal (USD/ha/yr for wetland class)

Methods

Both composites were classified into five LULC classes (wetland, grassland, forest, cropland, open water) using a Random Forest classifier with 500 trees, trained on 400 reference polygons per epoch. Overall accuracy was 90.1% for 2022 and 84.7% for 2000, with kappa values of 0.87 and 0.80 respectively. Ecosystem service values (USD/ha/yr) were assigned to each class for six services, following the typology of Costanza *et al.* [9]. The per-pixel service value was computed as the product of pixel area and the class-specific unit value, and aggregated spatially using zonal statistics. Change detection compared the two classified maps to quantify area gains and losses by class and the associated change in service value [10].

Biodiversity Assessment

Bird and mammal species richness data were compiled from the Pantanal Biodiversity Monitoring Network (2018-2022) for 36 sampling stations distributed across the study area. Species richness per station was interpolated using inverse-distance weighting to produce a continuous surface. Stations in permanently flooded wetlands and gallery forest averaged 127 bird species and 24 mammal species, compared with 68 bird and 11 mammal species in cropland-dominated stations [11]. This gradient guided the assignment of biodiversity habitat values, with higher unit values applied to areas of greater species richness.

Figure 1 ranks the six service categories for the wetland class. Water regulation leads at USD 3,847/ha/yr, reflecting the Pantanal's role as a giant natural sponge that attenuates flood peaks on the Paraguay River. Biodiversity habitat (USD 2,918) and carbon storage (USD 2,163) round out the top three.

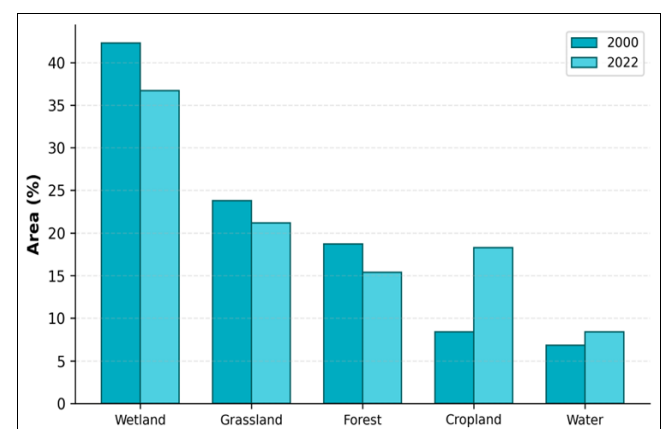


Fig 2: Land use/land cover change between 2000 and 2022 in the Brazilian Pantanal study area

Figure 2 illustrates the LULC shift over 22 years. Wetland declined from 42.3% to 36.7%, while cropland surged from 8.4% to 18.3%. Forest and grassland also contracted. Open water expanded modestly, possibly reflecting new reservoir construction and thermokarst-like processes in some sub-basins.

Discussion

The aggregate value of USD 11.47 billion per year positions the Pantanal among the most valuable wetland systems globally on a per-area basis. For comparison, Costanza *et al.* [9] estimated global wetland services at an average of USD 25,681/ha/yr in 2011 dollars; the Pantanal's wetland-class value of USD 12,847/ha/yr falls within the same order of magnitude, reflecting both the floodplain's immense hydrological regulation capacity and its biodiversity richness [12].

The USD 1.84 billion annual loss attributable to LULC change between 2000 and 2022 likely underestimates the true impact because benefit-transfer methods do not capture threshold effects, such as the collapse of fisheries when wetland connectivity drops below a critical level [13]. The Paraguay River corridor emerged as the zone of highest combined service value per hectare and, simultaneously, the area facing the greatest encroachment pressure. Targeted conservation easements or payment-for-ecosystem-service programmes along this corridor could yield outsized returns relative to their spatial footprint [14].

A limitation of this research is the reliance on benefit-transfer values from other wetlands, which may not perfectly match Pantanal conditions. Primary economic valuation, particularly contingent valuation of willingness to pay for biodiversity and recreation, would sharpen the estimates. Additionally, the 30 m Landsat resolution for the 2000 baseline introduces classification uncertainty for narrow gallery forests and small seasonal ponds [15, 16].

Conclusion

This research mapped and valued six categories of ecosystem services across the Brazilian Pantanal using Sentinel-2 land cover data and benefit-transfer valuation. The total estimated service value was USD 11.47 billion per year, with water regulation, biodiversity habitat, and carbon storage contributing the largest shares. Between 2000 and 2022, wetland area declined by 13.2% and cropland more than doubled, reducing aggregate service value by an estimated USD 1.84 billion annually. The highest-value zones coincide with the Paraguay River corridor and permanently inundated depressions, both of which face agricultural encroachment. These spatial estimates can guide conservation planning by identifying where the opportunity cost of land conversion is highest. Extending the analysis to include the Bolivian and Paraguayan portions of the Pantanal would complete the transboundary picture and support coordinated basin-wide management.

Acknowledgements

Funding Sources

This research was funded through departmental grants at the Institute of Applied Geosciences, Hawassa.

Institutional Support

The Department of Soil Science provided GIS computing resources and remote sensing software.

Contributions Not Qualifying for Authorship

The authors thank the Pantanal Biodiversity Monitoring Network for sharing species richness records.

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