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Quantifying the extent and rates of change in wetland ecosystem functional groups in the Maputaland Coastal Plain of South Africa

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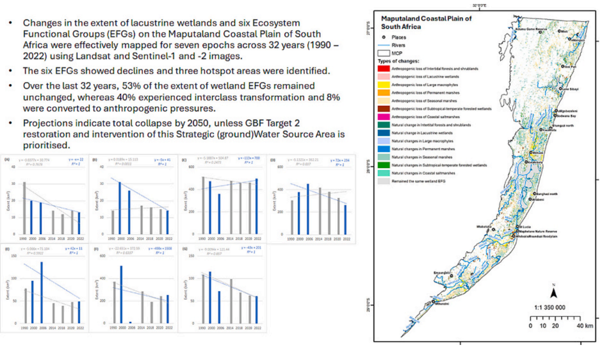
HIGHLIGHTS

- EO images at a ≤10 m spatial resolution is critical for monitoring palustrine wetland ecosystem types.
- The six palustrine wetland EFGs exhibited a downward trend with an increasing loss after 2006.
- Intertidal and forested wetlands showed a high rate of decline over seven epochs.
- Natural and anthropogenic pressures cause changes in the extent of EFGs.
- High losses occurred between the areas of Vasi Pan and eManguzi, KwaMbila and the iMfolozi/uMsunduzi floodplain.

GRAPHICAL ABSTRACT



- Changes in the extent of lacustrine wetlands and six Ecosystem Functional Groups (EFGs) on the Maputaland Coastal Plain of South Africa were effectively mapped for seven epochs across 32 years (1990 – 2022) using Landsat and Sentinel-1 and -2 images.
- The six EFGs showed declines and three hotspot areas were identified.
- Over the last 32 years, 53% of the extent of wetland EFGs remained unchanged, whereas 40% experienced interclass transformation and 8% were converted to anthropogenic pressures.
- Projections indicate total collapse by 2050, unless GBF Target 2 restoration and intervention of this Strategic (ground)Water Source Area is prioritised.

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ABSTRACT

Despite global concerns highlighting the threats to wetlands, monitoring and quantifying changes in palustrine wetland ecosystem extent remains inadequate. The feasibility of mapping the extent and rates of change of wetland Ecosystem Functional Groups (EFGs) in the Maputaland Coastal Plain, South Africa, using Earth Observation (EO) was evaluated. Seven wetland EFGs were mapped, including two estuarine (Coastal saltmarshes, and Intertidal forests and shrublands (mangroves)) and five freshwater EFGs (Lacustrine wetlands and palustrine wetlands: Large macrophytes, Permanent marshes, Seasonal marshes, and Subtropical-temperate forested wetlands). Changes in their extent were quantified across seven epochs across a 32-year period (1990–2022), including three above-average rainfall years (2000, 2006, and 2022), and four years that corresponded with the South African National Land Cover datasets (SANLCs: 1990, 2014, 2018, and 2020). Landsat images between 1990 and 2014 and a combination of Sentinel-1 and -2 images between 2018 and 2022 were modelled with a Random Forest classifier using EFG reference spectra informed by fieldwork. The classifications achieved overall accuracies between 78% and 87%, with user accuracies of the EFGs ≥ 73% for all years. Over the last 32 years, 53% of the extent of wetland EFGs remained unchanged, whereas 35% experienced interclass transformation and 8% were converted to anthropogenic pressures (5% speckle ignored). Four of the wetland EFGs showed an annual decline of 1% to 3%. Projections indicate that, under current conditions, four EFGs could

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face total collapse by 2050, with Intertidal forests and shrublands at the highest risk. The findings highlight the need for enhanced EO-based monitoring and protective measures to preserve wetland biodiversity and its ecosystem services.

1. Introduction

Globally, the status of wetland ecosystems is an increasing concern, with evidence suggesting that they are highly threatened and the rate of losses is high (Davidson, 2014; Davidson et al., 2019; IPBES, 2024; Convention on Wetlands, 2025). Moreover, global and local datasets mostly focus on changes in the extent of open water bodies and mangroves (Pekel et al., 2016; Bunting et al., 2022) and fall short of representing the diversity of palustrine wetland ecosystems and their dynamic changes over time. Consequently, current reports likely underestimate wetland loss.

Wetland extent changes are reported at the biome level (lacustrine or palustrine) for the Sustainable Development Goal (SDG) indicator 6.6.1a (Van Deventer, 2021), while wetland biodiversity types will be reported in 2030 to the Global Biodiversity Framework (GBF). Under Goal A of the GBF, Targets 1–3 aim to (i) 'Plan and manage all areas to reduce biodiversity loss', (ii) 'Restore 30% of all degraded ecosystems', and (iii) 'Conserve 30% of land, waters and seas' (CBD, 2023). The extents and rates of changes are also criteria used in the Red Listing of Ecosystems (RLE; IUCN, 2024), which are considered as the first indicator under the GBF Target 1, together with the extent ranges of ecosystems. The quantification and detection of changes in the extent of three wetland types, including open water bodies (Pekel et al., 2016), Intertidal forests and shrublands or mangroves (Bunting et al., 2022; Worthington et al., 2024), and saltmarshes (as part of tidal wetlands; Murray et al., 2022), have been globally done via Earth Observation (EO). Other wetland biodiversity types listed in the Global Ecosystem Typology (GET; Keith et al., 2022) for GBF reporting, such as forested wetlands, and Permanent or Seasonal marshlands, have recently been predicted for Africa and globally (Li et al., 2022; Zhang et al., 2023, 2024).

The underrepresentation of global datasets inadequately reporting and monitoring wetland types at the biome and EFG levels is illustrated in three South African studies. The Global Surface Water products (Pekel et al., 2016) represented only 11–13% of the extent of wetlands in the National Wetland Map version 5, of which 2% represented the fringes of lacustrine systems that seasonally inundate and host vegetation (Van Deventer, 2021). The extent of palustrine wetlands was estimated to cover 55% of the total extent of all natural wetlands, whereas shallow or small lacustrine wetlands in the arid regions, which are not regularly inundated and poorly represented in the global datasets, totalled 34% (Van Deventer et al., 2020). The efficiency of detecting changes in lacustrine and palustrine wetland types, at EFG level is therefore critical at a fine-scale level, to assess whether improvements in global models can be made for improved reporting to the GBF.

The Maputaland Coastal Plain (MCP) in South Africa is an 8141 km^2 area at the southern tip of the Mozambican coastal plain, that hosts diverse wetland ecosystem types, ranging from the estuarine systems along the coast to freshwater systems inland (Taylor et al., 2006; Colvin et al., 2003; Ndlovu and Demlie, 2018). Previous studies have mapped wetland EFG types within the MCP, but these studies have been limited in their geographical coverage of the MCP, the diversity of the EFGs covered or quantification of the types and aerial extent of changes (Adam and Mutanga, 2009; Grundling et al., 2013; Lück-Vogel et al., 2016; Van Deventer et al., 2019, 2021; Slagter et al., 2020). Several authors have raised concerns about the anthropogenic and climate change pressures on the MCP. A total of 34 peatlands had shown evidence of increased desiccation and, in some instances, peat fires since the most recent 2015/16 drought across the landscape (Grundling et al., 2021). In the northern part of the MCP, the increase in timber plantations has resulted in a decline in the extent of lacustrine wetlands, which coincided with a decadal drought (Adams et al., 2016; Adams, 2020; Ramjeawon et al., 2020). Even though 28% of the extent of the MCP is formally located in protected areas (Van Deventer et al., 2021), visual evidence of transformation from forested and marsh wetlands to agriculture raised concerns about the extent and rate of transformation and losses. Concerns about the decline of forested wetlands have prompted their nomination as a critically endangered ecosystem (Van Deventer et al., 2021). The full impact of the various pressures across the landscape on all the wetland EFGs, over time, is deficient.

This study aims to identify and quantify the aerial extent, types and location of changes in all the wetland EFGs of the MCP. The first hypothesis is that the Landsat and Sentinel-1 and -2 images can delineate and detect the impacts of pressures on wetland biodiversity types to support improved reporting to the GBF. The second hypothesis is that some wetland ecosystem types are more subject to natural hydrological, anthropogenic and/or climate changes than others. The assessment of the full extent of the MCP is critical, to ensure full representation of wetland ecosystem types of this region, understanding the dynamics of different EFGs, to evaluate EO as an effective monitoring tool for RLE assessments and to inform required restoration interventions.

2. Methods

2.1. Description of the study area

The MCP is a region located on the north-eastern coast of South Africa within the KwaZulu-Natal Province, encompassing an area of 8141 km^2, with geographic coordinates spanning between 29°13′22.913″ S and 26°50′56.266″ S latitude and between 31°30′19.69″ E and 32°53′27.806″ E longitude (Fig. 1). The study area is bound by the border of Mozambique in the north and extends down to the uThukela River Estuary in the south, with the Indian Ocean serving as its eastern boundary and the Lebombo Mountains in the west. In the eastern part, the annual rainfall ranges from 1000 mm to 1300 mm, whereas the western areas receive an average annual rainfall of approximately 900 mm (Bailey and Pitman, 2016). However, this pattern can be variable due to the MCP's susceptibility to extreme rainfall events, such as tropical cyclones and cut-off low-pressure systems, which can cause annual fluctuations in rainfall totals (Blamey and Reason, 2023). The MCP gradually transitions from a temperate climate zone in the south to a subtropical climate zone in the north (Mucina and Rutherford, 2006). The region, on average, is approximately 60 m above mean sea level and has gentle terrain, with the highest elevation of 700 m near the Lebombo Mountains on the western edge (Van Deventer et al., 2021).

The geomorphology of the MCP is shaped by its position on the Indian Ocean coastline, with sandy beaches, dunes, and estuaries along the eastern edge and a series of low hills and ridges of the Lebombo Mountains along the western edge (Mucina and Rutherford, 2006). The geology of the region is primarily composed of basalt and rhyolite lava that underlie the coastal plain and are overlain by conglomerates, sandstones and recent reworked coastal sandy sediments on the surface (Botha and Porat, 2007). A variety of biomes, including azonal vegetation, forests, the Indian coastal belt, savanna, and wetland biomes, occur in the MCP (Dayaram et al., 2019; Van Deventer et al., 2020). Terrestrial vegetation types include forest types such as coastal, dune, mangrove, riverine, sand, scarp and swamp forests, as well as grasslands (Dayaram et al., 2019).

Wetlands in the MCP range from groundwater-fed to surface water-fed fens and floodplains (Kelbe and Germishuyse, 2001; Grundling et al., 2013; Le Maitre et al., 2018). The wetlands overlie and sometimes

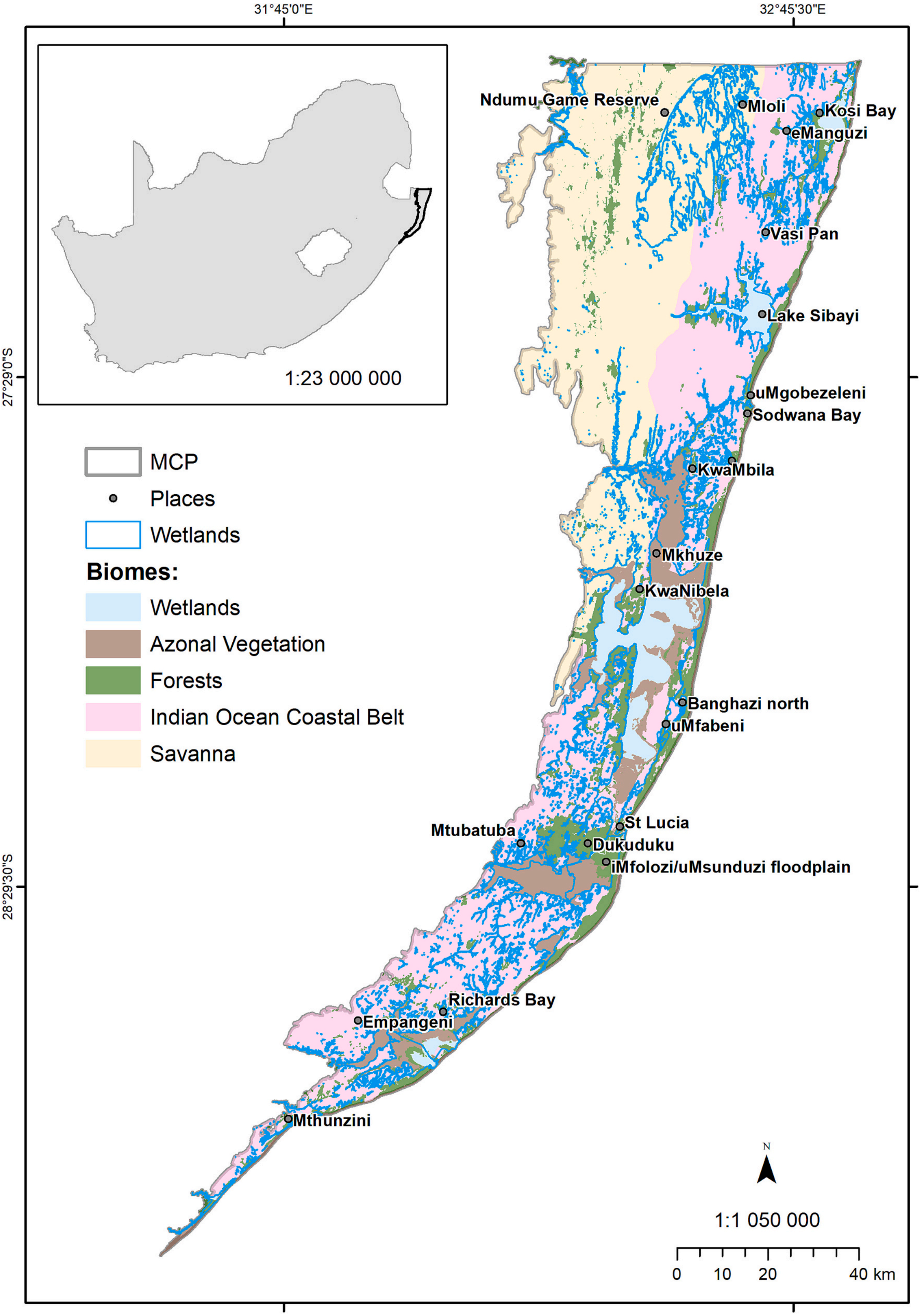

Fig. 1. Location of the Maputaland Coastal Plain (MCP) relative to (A) South Africa, providing (B) an overview of the MCP showing the extent of wetlands mapped in the National Wetland Map version 6 (SANBI, 2024), some key vegetation biomes (Dayaram et al., 2019) and main landmarks and towns.

connect to the underlying regional water table, which slopes towards the Indian Ocean (Grundling, 2014). Permanent wetlands are found in groundwater discharge zones in lowland areas and usually have peat or highly organic substrates, whereas temporary wetlands are associated with regional fluctuations in the water table (Kelbe et al., 2016).

2.2. Analysis

The analysis and assessments of the accuracies related to this paper, is described in Apleni et al. (2026).

3. Results

3.1. Variation in the extent, distribution, and geographic location of wetland Ecosystem Functional Groups across the MCP

Between 1990 and 2022, the extent of wetland EFGs in the MCP varied, ranging from a minimum of 1065 km^2 (13% of the extent of the MCP) in 2006 to a maximum of 1420 km^2 (17% of the extent of the MCP) in 1990 (Table 1; Fig. 2). Notably, lacustrine wetlands consistently dominated throughout all years relative to the total extent of the MCP, with an average extent of 463 km^2 (6% of the extent of the MCP). The estuarine and palustrine types, on the other hand, had an average extent of 202 km^2 (2% of the extent of the MCP; Table 1). Among the palustrine wetland EFGs, Large macrophytes emerged as the most dominant in extent, with an area that varied from a minimum of 305 km^2 (4% of the extent of all wetland EFGs) in 1990 to a maximum of 326 km^2 (4% of all wetland EFGs) in 2018. In terms of marsh wetlands, Seasonal marshes were more prevalent in the notably wet year of 2000, which maximised to 512 km^2 (6% of the extent of the MCP) in extent, compared with the minimum extent of 252 km^2 (3% of the extent of the MCP) in 2022. In contrast, Permanent marshes experienced a substantial decline in extent over the years, reaching their peak at 137 km^2 (2% of the MCP) in 2000 but declining to 39 km^2 (0.47% of the MCP) by 2022 (Table 1; Fig. 2).

Over the assessed years, the northern distribution of wetland EFGs changed (Fig. 3). In 1990 and 2000, the northern distribution of EFGs had a dispersed arrangement, and in 2022, they had a concentrated arrangement near eManguzi. In contrast, the southern wetlands follow narrow distribution patterns along lake and river systems. Notably, in 2000, there was a notable abundance of seasonal floodplain marshes in the northern region, which gradually decreased in extent between 1990 and 2018 (Fig. 3).

3.2. Accuracy assessment of the EO classification of wetland ecosystem functional groups

For the first four years (1990, 2000, 2006 and 2014), the overall accuracy (OA) of the classification ranged from 78.1% to 81.9%, with the average of these Landsat classifications being 80.5% (Table 2). In comparison, the three years that were classified via Sentinel-1 and Sentinel-2 (2018, 2020 and 2022) achieved OAs ranging from 82.2% to 87.0%, with average OAs of 84.5%, which were 4% higher than the average OAs attained in the four Landsat classifications.

Across all years, all four palustrine wetland EFGs (Large macrophytes, Permanent and Seasonal marshes, and subtropical-temperate forested wetlands) attained user accuracies of ≥73.8% and ≥78.0% when not considering the 1990 classification (Table 2). Among all the wetland EFGs across all seven years, Intertidal forests and shrublands (mangrove forests) achieved the highest user and producer accuracies, with a peak of 98.9% producer accuracy in 2018 and 98.5% user accuracy in 2022.

Conversely, Coastal saltmarshes exhibited the greatest variation in producer's and user's accuracies, ranging from 64.8% to 83.3% for producer accuracy and 78.6% to 91.9% for user accuracy across the seven classification years. Seasonal and Permanent marshes also showed considerable variation, with producer accuracies ranging from 73.9% to 86.4% and user accuracies ranging from 73.8% to 84.8%.

Lacustrine wetlands improved in accuracy over time, with both producer and user accuracies increasing from 1990 to 2022. The producer accuracy improved from 80.4% in 1990 to 95.0% in 2022, whereas the user accuracy increased from 87.4% to 90.4% over the same period. Large macrophytes consistently achieved high producer accuracies (>90%) across all years, ranging from 91.5% to 93.8%. The user accuracies for this class remained stable at approximately 80%, with a range of 79.9% to 82.3%. In general, the overall accuracies showed an increase from 1990 to 2022, starting at 78.1% in 1990 and reaching the highest accuracy of 87.0% in 2022, the most recent classification year.

3.3. Changes in the extent of wetland EFGs over time

Analysing the trends across the seven wetland EFGs, a general pattern of decline is evident in all the categories over the 32-year period from 1990 to 2022. Coastal saltmarsh (Fig. 2A), Intertidal forests and shrublands (Fig. 2B), Large macrophytes (Fig. 2C), Permanent marshes (Fig. 2E), and Subtropical-temperate forested wetlands (Fig. 2G) all show overall decreasing trends, with varying degrees of fluctuation. Lacustrine wetlands (Fig. 2C) showed a stable trend, whereas Seasonal marshes (Fig. 2F) had a more complex pattern with fluctuations, including sharp declines followed by partial recoveries.

The Coastal saltmarsh (Fig. 2A) has the strongest linear relationship, with $R^2 = 0.9$, suggesting a consistent decline. They were followed by subtropical-temperate forested wetlands and Permanent marshes, which had moderately strong linear trends ($R^2 = 0.65$ and 0.35, respectively). In contrast, Intertidal forests and shrublands, lacustrine wetlands, Large macrophytes, and Seasonal marshes have low R^2 values (ranging from 0.01 to 0.17).

3.4. Types and extent of changes observed between 1990 and 2022

Among the wetland EFGs, Permanent marshes and Coastal

Table 1
Extent of wetland Ecosystem Functional Groups (EFGs) on the Maputaland Coastal Plain (MCP) between 1990 and 2022.

Wetland EFG	1990		2000		2006		2014		2018		2020		2022	
	km^2	% of MCP	km^2	% of MCP	km^2	% of MCP	km^2	% of MCP	km^2	% of MCP	km^2	% of MCP	km^2	% of MCP
Coastal salt marsh	31	0	20	0	19	0	14	0	12	0	14	0	13	0
Intertidal forests and shrublands	14	0	31	0	26	0	17	0	16	0	15	0	14	0
Lacustrine wetlands	513	6	474	6	361	4	476	6	458	6	460	6	498	6
Large macrophytes	305	4	378	5	450	6	418	5	381	5	326	4	263	3
Permanent marshes	78	1	95	1	137	2	45	1	39	0	48	1	49	1
Seasonal marshes	370	5	512	6	14	0	284	3	193	2	243	3	252	3
Subtropical-temperate forested wetlands	109	1	115	1	72	1	99	1	69	1	62	1	61	1
Total extent	1,420	17	1,625	20	1,065	13	1,353	17	1,168	14	1,168	14	1,150	14

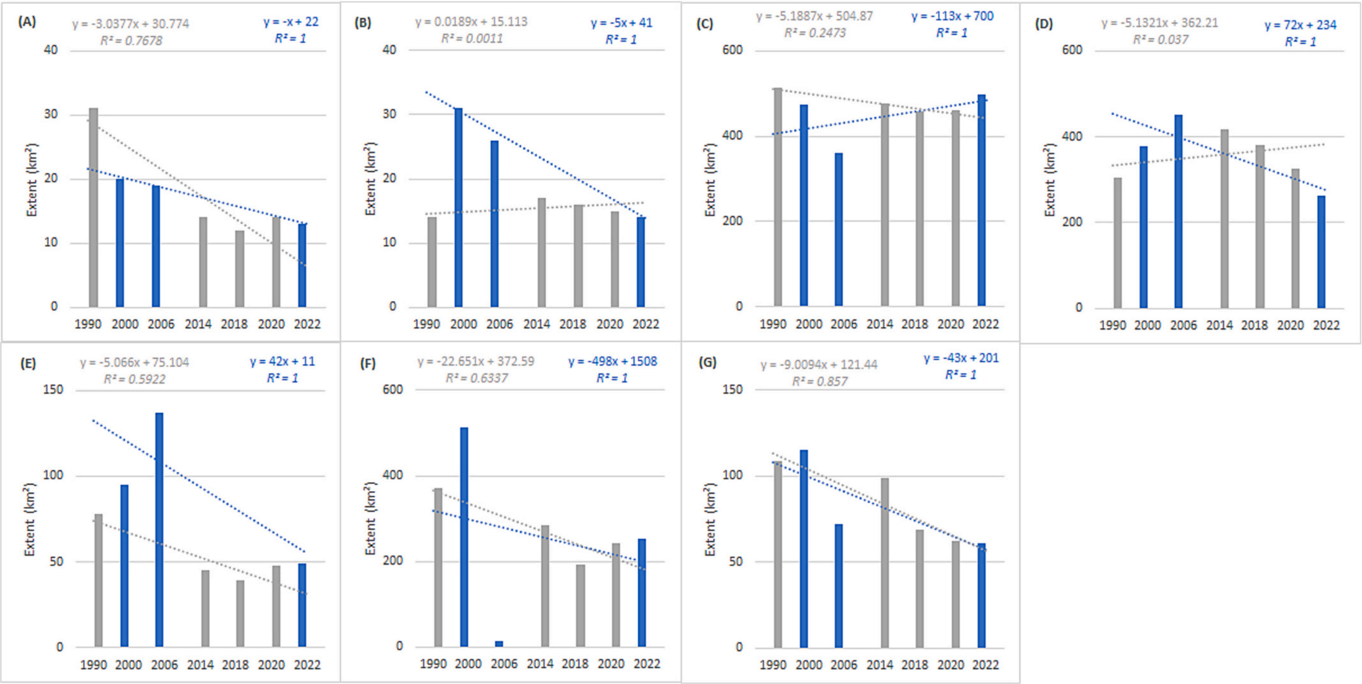

Fig. 2. Trend graphs depicting rates of change in the extent of palustrine wetland Ecosystem Functional Groups (EFGs) for seven epochs across a 32-year period on the Maputaland Coastal Plain, showing differences in (i) the wet and dry epochs and (ii) confidence ranges per epoch for different EFGs. EFGs include (A) Coastal saltmarshes, (B) Intertidal forests and shrublands or mangroves, (C) Lacustrine wetlands, (D) Large macrophytes, (E) Permanent marshes, (F) Seasonal marshes and (G) Subtropical-temperate forested wetlands.

saltmarshes experienced the most pronounced changes. By 2022, less than 10% of the original 1990 extent of both classes remained (Fig. 4A). Permanent marshes experienced a 32% transition to terrestrial grasses, whereas Coastal saltmarshes underwent several transitions, including 26% shifting to Intertidal forests and shrublands and 31% changing to Large macrophytes (Fig. 4A). Most transitions within wetland EFGs were inter-wetland changes. The Seasonal marshes experienced a 25% transition to terrestrial grasses. Anthropogenic changes were also observed and were mostly related to timber plantations, and mostly affected freshwater wetland EFGs. For example, the highest transformation due to anthropogenic change was due to 8% of the Seasonal marshes being replaced by timber plantations. Notably, some wetland classes presented transitions that suggest misclassifications, such as 8% Subtropical–temperate forested wetlands transitioning to coastal forests. Values less than 5% were discarded because of image or classification artifacts such as speckle. The results are summarised in Fig. 4B. Overall, 52.9% of the wetlands remained in the same wetland EFG category, whereas 19.6% changed to terrestrial classes. Approximately 8.9% changed from estuarine to freshwater, whereas approximately 8.1% were transformed to anthropogenic classes (Fig. 4B).

This study also identified regions of high transformation of wetland ecosystem functional groups within the MCP. These areas showed a loss of wetland EFGs to terrestrial classes and another wetland EFGs (Fig. 5A). Between Vasi Pan and eManguzi, many wetland EFGs that were present in 1990 changed to terrestrial classes such as grasslands and shrublands (Fig. 5B). Similarly, the KwaMbila area also included large areas where seasonal wetland EFGs changed to terrestrial classes (Fig. 5C). The transformation in the eastern part of the iMfolozi/uMsunduzi floodplain, on the other hand, was mostly due to changes from forested wetlands to Large macrophytes (Fig. 5D).

3.5. *Rates of change in wetland ecosystem functional groups*

Overall, the analysis of wetland EFG rate changes revealed a downward trend for Coastal saltmarshes, Intertidal forests and shrublands, Large macrophytes, and Subtropical-temperate forested wetlands (Fig. 6A). Coastal saltmarshes, despite a significant 8% increase per year from 2018 to 2020, exhibited an overall average decline of −1% per year between 1990 and 2022 relative to their 1990 extent (Fig. 6A). Intertidal forests and shrublands began with an 8% increase per year from 1990 to 2000, but subsequent years displayed a downward trend, with the most substantial decrease of −5% occurring between 2014 and 2018, leading to an average annual rate of −1% (Fig. 6A). Large macrophytes sharply decreased by −11% per year between 2018 and 2020, which contributed to an average rate of −3% per year, despite initial positive rates of 2% and 3% between 1990 and 2000, respectively. Subtropical–temperate forested wetlands have consistently declined over time, culminating in an average rate of −3% per year. In contrast, Permanent marshes and Seasonal marshes experienced variable rates across all seven time periods assessed, whereas lacustrine wetlands exhibited minimal fluctuations, maintaining an average rate of 0% per year.

The estimates of the absolute rates of change of the wetland ecosystem groups revealed that four out of the six palustrine wetland types (Intertidal forests and shrublands, Permanent marshes, Seasonal marshes, and Subtropical-temperate forested wetlands) are headed for total collapse if current trends continue and if no action is taken to address the pressures on the MCP (Fig. 6B).

4. Discussion

This study leverages multi-decadal Landsat and Sentinel-1 and -2 imagery to analyse changes in wetland EFGs across the MCP from 1990 to 2022. By examining the spatial and temporal dynamics of wetland types, this research provides critical insights into the utility of these EO platforms for long-term wetland monitoring. The first hypothesis argued that Landsat and Sentinel-1 and -2 images can delineate and detect the impacts of pressures on wetland biodiversity types to support improved reporting to the GBF. This proved to be successful for this study area and

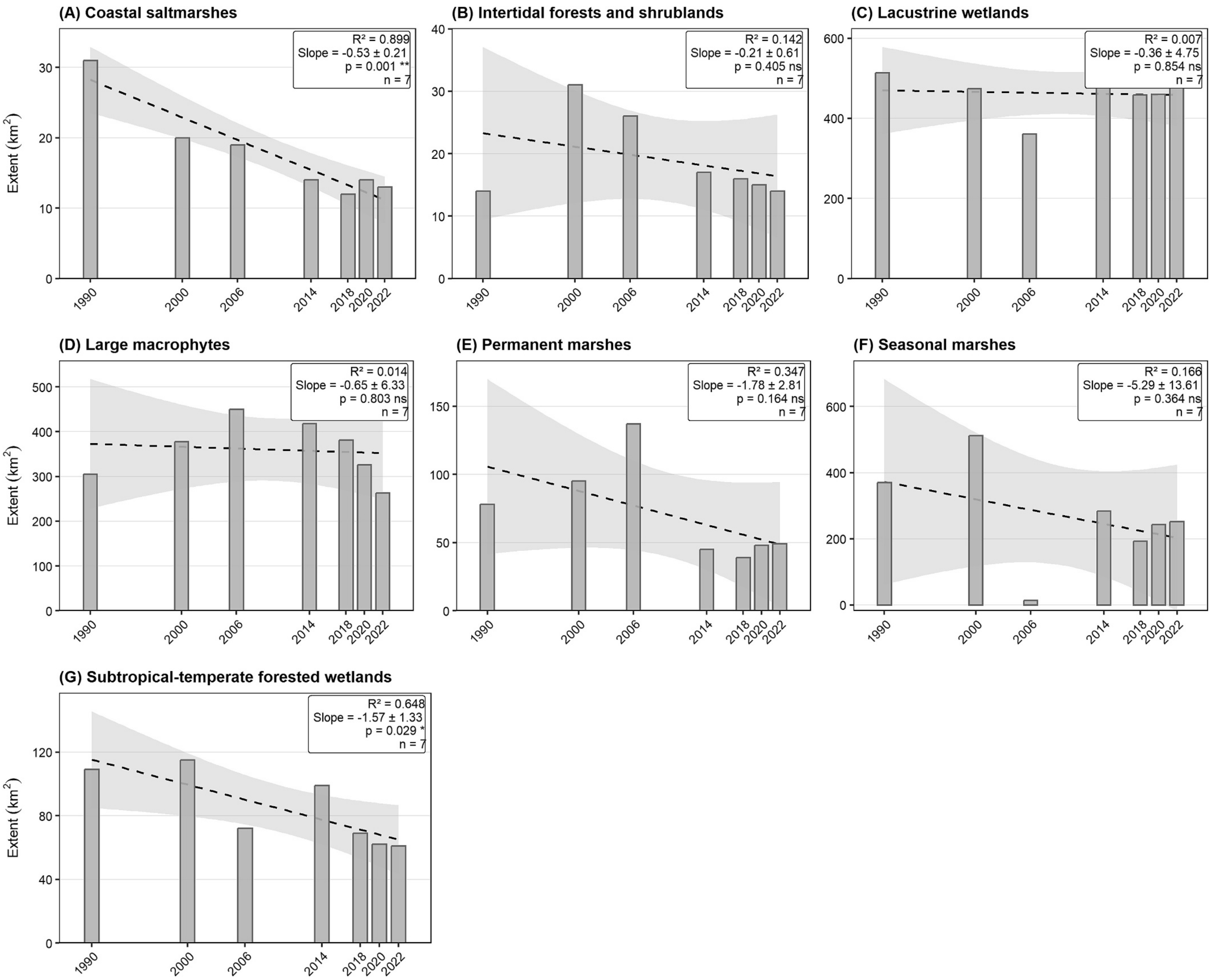

Fig. 2. (*continued*).

EFGs, yet some challenges and shortcomings remain, which are discussed below. In addition, the validity of this hypothesis remains to be tested in other environments for the EFGs of palustrine wetlands.

The second hypothesis is that some wetland ecosystem types are more subject to natural hydrological, anthropogenic and/or climate changes than others. Coastal saltmarshes, Large macrophytes, and the Permanent and Seasonal marshes show fluctuations in extent that may result from natural changes in the environment, including rainfall and changes in groundwater levels. The extent of Coastal saltmarshes and Large macrophytes near estuarine environments is also influenced by estuarine mouth states. In contrast, the Intertidal forests and shrublands (mangroves) and Subtropical-temperate forested wetlands are expected to show slight increases over time in extent, despite being bound by environmental conditions. Both these forest types show declines in extent. Drivers of these changes are further discussed below.

The study also explores the implications of these findings for the reporting in ecosystem frameworks, such as the RLE (IUCN, 2024) which is considered the first indicator of Target 1 of the GBF, and the SDGs 6.6.1a indicator, as well as reporting to targets 2 (restoration) and target 3 (protection levels) of the GBF at national and global scales.

4.1. Suitability of Landsat and Sentinel-1 and -2 for monitoring wetland EFGs

The combined use of Landsat and Sentinel datasets proved effective for monitoring MCPs' diverse wetland EFGs, achieving classification accuracies between 78% and 87% over the study period. Landsat's multi-decadal archive enabled the historical analysis of wetland dynamics, whereas Sentinel-1's SAR capabilities and Sentinel-2's higher spatial and spectral resolutions provided enhanced classification accuracy, particularly in recent years. Previous studies, such as those by Mahdianpari et al. (2020) and Slagter et al. (2020), similarly demonstrated the advantages of Sentinel-2's spectral richness and SAR data for capturing structure and composition within wetlands, validating the findings of this study. The first hypothesis is therefore supported, with fine-scale infield validation that can serve as reference material for global modelling and change detection of the palustrine wetland biome, and four EFGs, including forested wetlands, Large macrophytes, as well as Permanent and Seasonal marshes.

While Landsat data offered essential continuity, its moderate 30-m spatial resolution limited the detection of small or fragmented wetland patches, especially palustrine wetland EFGs. A major challenge that is presented for RLE and GBF reporting is the over-prediction of the reference state of these wetland EFGs. However, Sentinel-2's 10-m

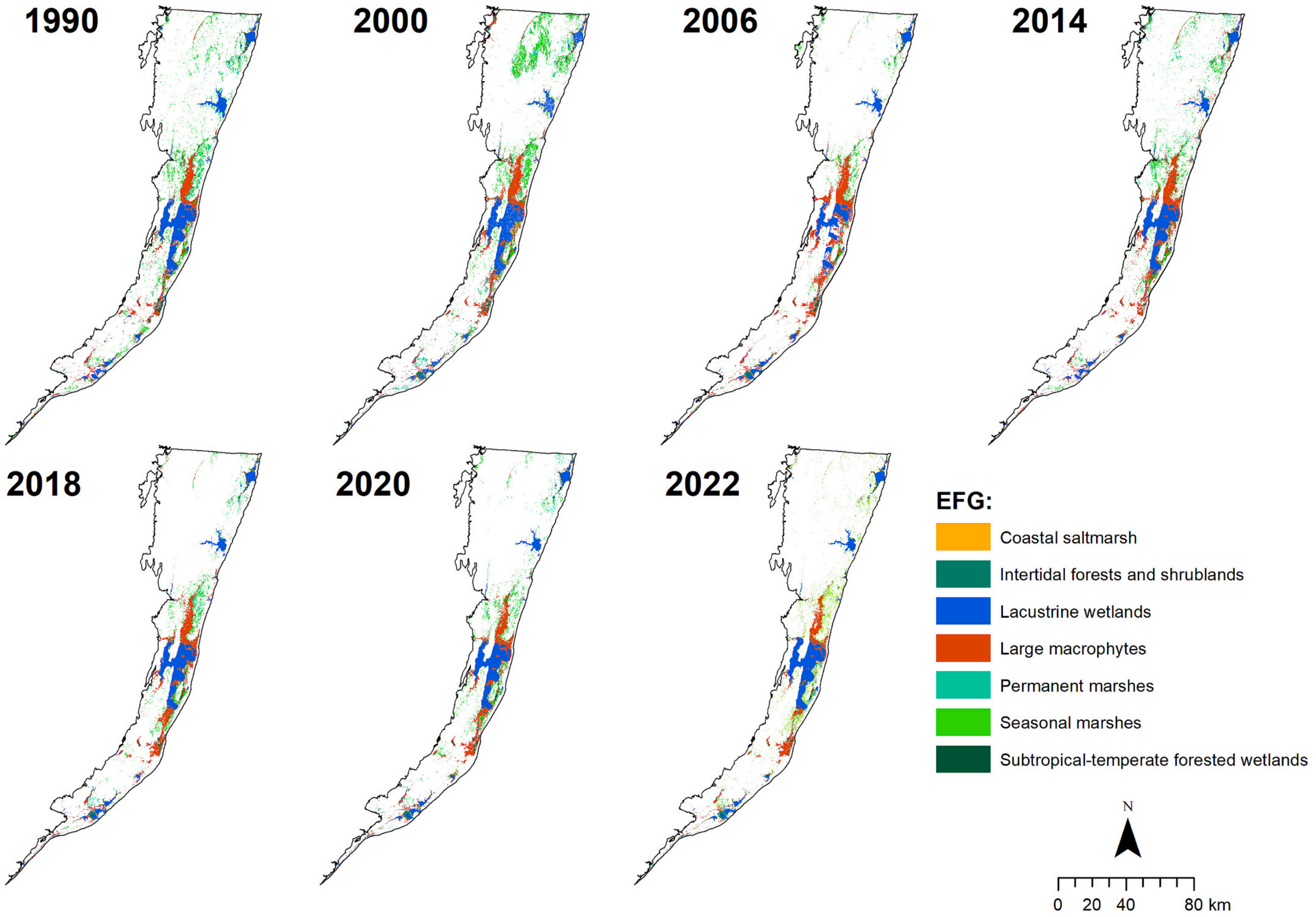

Fig. 3. Changes in the extent (%) and type of wetland Ecosystem Functional Groups in Maputaland Coastal Plain between 1990 and 2022. The grey areas represent transformations of less than 5%.

Table 2
A summary of the accuracy assessment of wetland Ecosystem Functional Groups of the Maputaland coastal plain, listing the percentages (%) of overall accuracy (OA), producer accuracy (PA), and user accuracy (UA) between 1990 and 2022.

Year/ epoch	Accuracy	Coastal saltmarshes	Intertidal forests and shrublands	Lacustrine wetlands	Large macrophytes	Permanent/seasonal marshes	Subtropical-temperate forested wetlands
1990	OA	78.1					
	PA	68.5	94.1	80.4	91.5	80.9	78.8
	UA	82.1	94.6	87.4	82.3	73.8	83.4
2000	OA	81.4					
	PA	83.3	95.3	85.0	92.1	83.4	78.1
	UA	83.3	94.7	82.0	80.9	80.6	75.9
2006	OA	81.9					
	PA	80.5	96.5	86.8	93.8	79.4	81.2
	UA	89.6	93.6	88.4	80.9	78.0	85.3
2014	OA	80.7					
	PA	78.6	94.7	74.6	92.2	73.9	79.9
	UA	78.6	92.0	76.5	81.0	80.0	86.0
2018	OA	82.2					
	PA	73.3	98.9	82.4	93.7	77.3	82.4
	UA	85.1	97.1	88.6	80.7	84.8	85.2
2020	OA	84.2					
	PA	64.8	98.0	93.8	92.8	86.4	82.2
	UA	91.9	94.9	92.8	79.9	78.1	81.9
2022	OA	87.0					
	PA	69.9	95.6	95.0	93.8	86.4	76.0
	UA	84.0	98.5	90.4	80.3	83.0	92.0

spatial resolution addresses these limitations, enabling finer delineation of EFGs such as Seasonal marshes, and Intertidal forests and shrublands. The dual-polarisation capability of Sentinel-1 SAR further enhances classification by distinguishing vegetation structure differences, an advantage underscored by Slagter et al. (2020), who reported that SAR-optical data fusion is effective in complex wetland landscapes. These

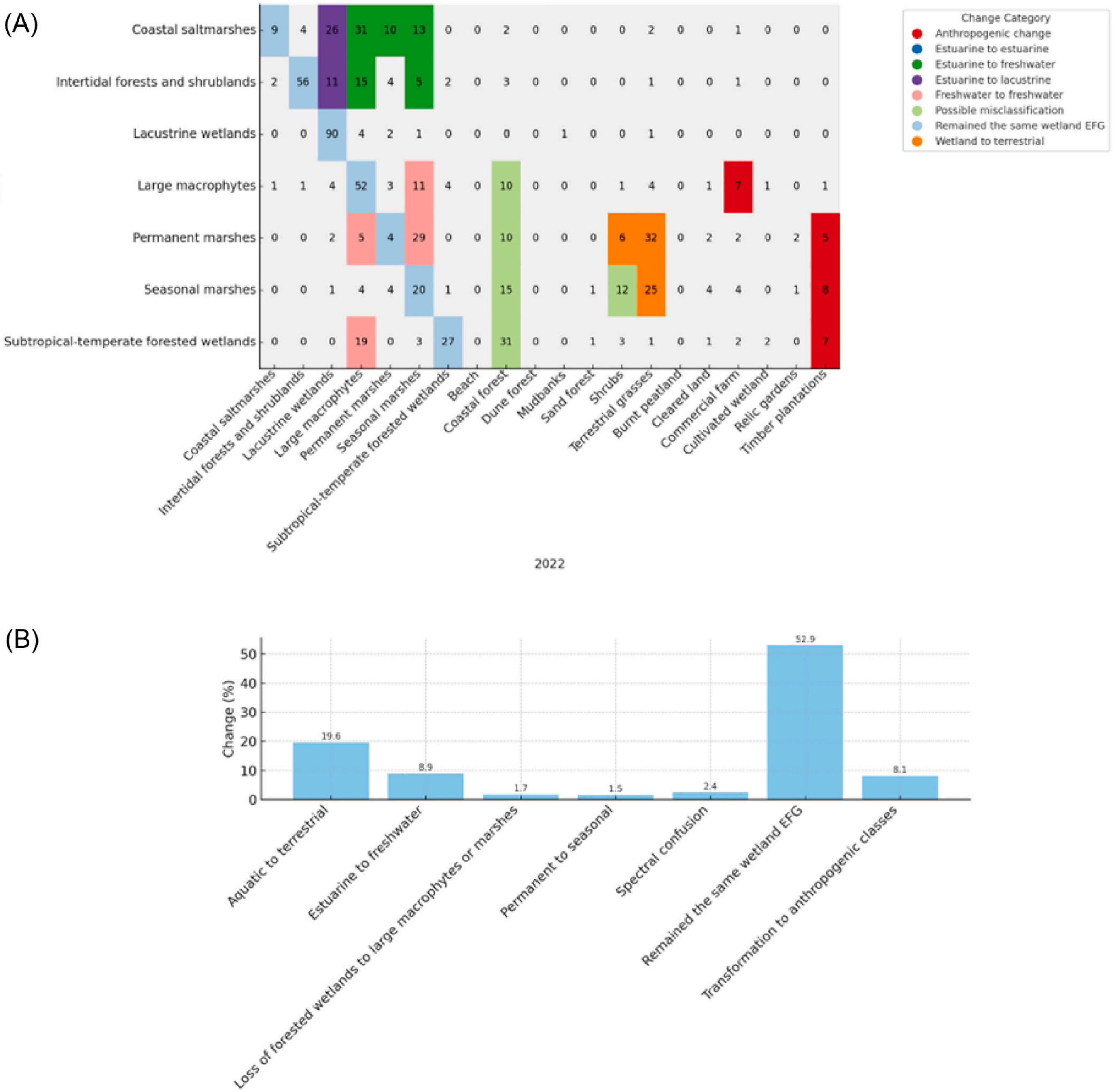

Fig. 4. (A) Changes in the extent (%) and type of wetland Ecosystem Functional Groups in Maputaland Coastal Plain between 1990 and 2022. The grey areas represent transformations of less than 5%. (B) Summary of the transition matrix of wetland ecosystem functional groups (EFGs) between 1990 and 2022.

results confirm that Landsat and Sentinel data, when integrated with machine learning classifiers such as random forest, are suitable and robust for long-term wetland EFG monitoring.

The major limitation in this study was the limited availability of historical Landsat datasets in the MCP, and the coarse-scale resolution data as reference extents. Data from the 1980s were limited and mostly had high cloud cover, and composites of the whole MCP could not be generated. Additionally, the limited rainfall data from South African Weather Services in the MCP necessitated the use of CHIRPS data, which, while valuable, may not fully capture local rainfall patterns in the MCP. The study was limited to the transformation of wetland EFGs and did not consider degraded wetland EFGs. Future work can examine the degradation level of the wetland EFGs in the MCP. Additionally, while the results of this study revealed a 90% loss of Coastal saltmarshes, the results may be limited by tidal fluctuations, and future work can look at the changes in Coastal salt marshes with tidal influence as a factor. Where the majority of a pixel extent is covered by one EFG class, the extent may be overestimated in these historic Landsat images, which are used as a reference point of extent. The use of the Sentinel-1 and -2 images over longer periods of time, or comparisons between Landsat 8 and Sentinel-2 images at 30- and 10-m spatial resolution, respectively, may potentially illustrate the overestimation or error range in the delineation of extent and changes per class.

4.2. Comparison of user's and spatial accuracies of wetland EFGs with similar studies

The comparison of user's accuracies across wetland EFGs shows the

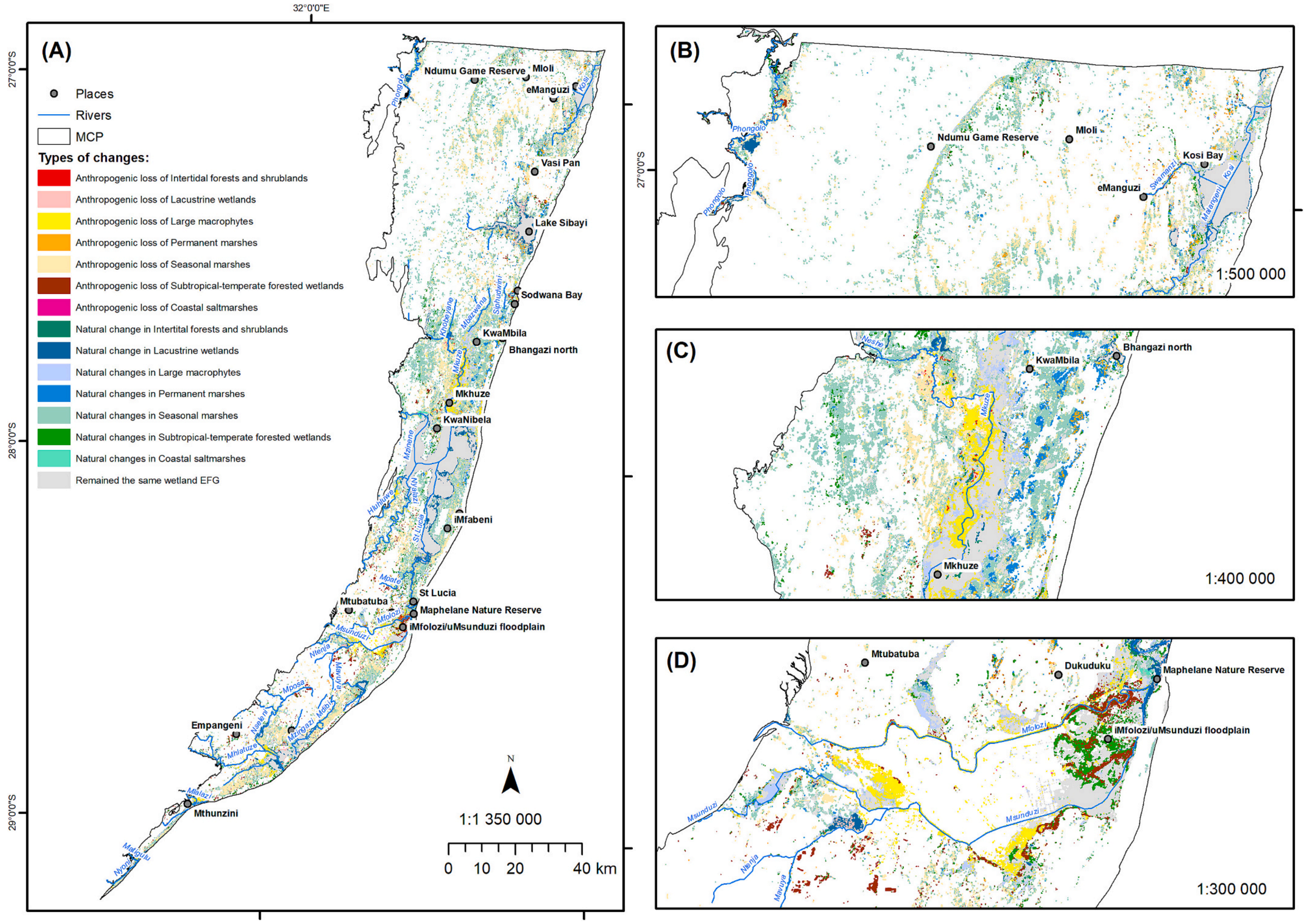

Fig. 5. (A) Areas where wetland ecosystem functional groups (EFGs) changed between 1990 and 2022 on the Maputaland Coastal Plain, showing (A) overall types of changes; (B) a hotspot area between Vasi Pan and eManguzi; (C) a hotspot area near KwaMbila; (D) and on the iMfolozi/uMsunduzi floodplain.

reliability of this study's classifications relative to other datasets. Coastal saltmarshes have a user's accuracy of 83%, which highlights the reliable identification of these ecosystems due to their unique spectral and structural signatures. The high accuracy of 94% for Intertidal forests and shrublands (mangroves) across highlights the effectiveness of this study's refined classification techniques, which surpass other datasets and benefit from enhanced spatial resolution that allows for precise differentiation in intertidal zones.

Permanent and Seasonal marshes achieved a user's accuracy of 80%, slightly above that of the Global Annual Wetland Dataset (Fig. B1, Supplementary material), although their seasonal variability presents inherent classification challenges, indicating potential gains from temporal data integration to capture seasonal shifts. For Subtropical-temperate forested wetlands, this study achieved 82% user's accuracy, higher than that of similar datasets, suggesting that regional dataset specificity may enhance classification precision in these areas. However, variability in other datasets points to the challenges posed by spectral overlap within this EFG.

The uMfabeni Swamp in the MCP was used as a case study in the MCP to compare this study's horizontal accuracy with that of other existing studies. Compared with those of other studies, the outputs from this study revealed the completeness and horizontal spatial accuracy of wetland EFGs in the uMfabeni Swamp (Fig. B2A, Supplementary material). Notably, it accurately mapped the extent (15 km^2) of the uMfabeni Swamp, capturing 100% of the Subtropical-temperate forested wetland class mapped by Venter (2003), which has been challenging for other studies (Zhang et al., 2023, 2024). For example, the SANLC 2014 mapped Subtropical-temperate forested wetland EFGs in uMfabeni as Indigenous Forests (2.5 km^2 and 16.4% of uMfabeni), Thicket/Dense Bush (0.23 km^2 and 1.39% of uMfabeni), or Timber Plantations (0.17 km^2 and 12.1% of the uMfabeni Swamp) (Fig. B2B, Supplementary material). A South African coastal ecosystem mapping study (Bessinger et al., 2022) (Fig. B2C, Supplementary material) did not classify Subtropical-temperate forested wetlands but instead classified 28.2% of the uMfabeni swamp as forest. The Global Wetlands Layer of 2020 (Fig. B2D, Supplementary material) missed 65% of the uMfabeni Swamp, mapping only 35.2% of the total area (4.9 km^2) and misclassifying Large macrophytes as Subtropical-temperate forested wetlands. These results, therefore, illustrate the completeness and accuracy of the results of this study.

4.3. *What are the drivers of wetland EFG changes in the MCP?*

The results from this study showed that the changes in wetland EFGs in the MCP could be due to both natural hydrological and climate variability, as well as anthropogenic changes. The periods of above-average rainfall, such as those observed in 2000, corresponded with temporary expansions of Seasonal marshes, which showed that climate fluctuations can lead to temporal gains or losses of some wetland EFGs. These patterns align with the findings of Grundling et al. (2013), who also showed that extreme weather events, including tropical cyclones, influence wetland dynamics in the MCP. These weather patterns are not consistent, because they are predominantly groundwater-dependent ecosystems rather than rainfall driven (Le Maitre et al., 2018). For

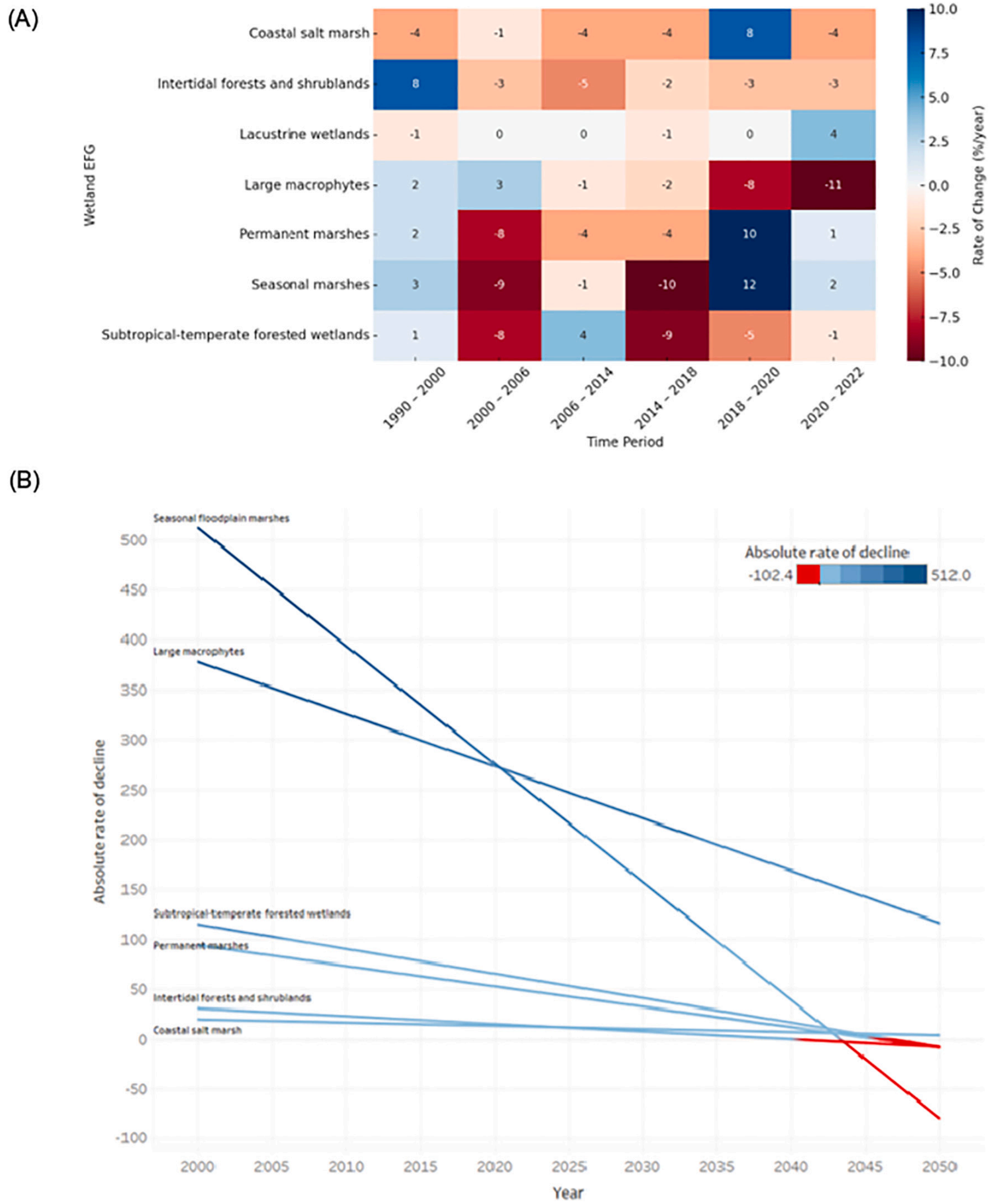

Fig. 6. Rates of change with (A) a heatmap showing rates of change in wetland Ecosystem Functional Groups (EFGs) between 1990 and 2022 for the seven years assessed in this study; and (B) the absolute rate of decline in six wetland EFGs in the Maputaland Coastal Plain of South Africa, as shown in the red list of ecosystem types.

instance, the extent of Seasonal marshes decreased markedly from 512 km^2 in 2000 to 14 km^2 in 2006. This substantial decline is consistent with Ramjeawon et al. (2020), who showed that the quaternary catchment W70A (the northern portion of the MCP) experienced the greatest wetland loss between 2001 and 2006, with annual reductions averaging 138 km^2. Although 2006 appears as a relatively wet year in the CHIRPS dataset, the decline observed here is unlikely to be an artifact of rainfall anomalies or an outlier-driven inflation of the CHIRPS mean. If elevated rainfall or short-term inundation had influenced the classification, one would expect Seasonal marshes to have been classified as palustrine wetlands. However, palustrine wetland extent did not show any corresponding increase during this period. Moreover, no major high-rainfall events were reported for 2006 that would support the presence of an outlier capable of pulling the CHIRPS average upward. Taken together, these lines of evidence suggest that the observed reduction reflects a genuine decline in Seasonal marsh extent rather than a rainfall-related or classification artifact. Other shifts, such as the 20% shift from aquatic to terrestrial classes, may look natural; however, in the context of the MCP, there is evidence of human influence together with climate change (Ndlovu and Demlie, 2020).

There is strong evidence that anthropogenic land cover changes, such as the introduction of timber plantations such as *Eucalyptus* spp.

and *Pinus* spp. can decrease the groundwater table, leading to drying of wetland EFGs (Kelbe and Germishuyse, 2010; Kelbe et al., 2016; Ndlovu and Demlie, 2018; Elshehawi et al., 2019; Everson, 2019; Grundling et al., 2021) and thus shifting the gradient towards terrestrial classes. The drying of wetlands due to the introduction of timber plantations may also be linked to the increase in the frequency and duration of peat fires in the MCP (Grundling et al., 2021). The 90% loss of Coastal saltmarshes between 1990 and 2022 is consistent with reports by Adams (2020), who reported that 67% of the supratidal saltmarsh area was lost near the Kosi Bay Lake system alone. These results also emphasise the monitoring of the whole MCP compared with small regional studies.

The rate and aerial extent of forested wetlands and mangroves under natural expansion in this 32-year period of assessment remain unclear. Georeferenced aerial photographs between 1942 and 2009 (Arndt, 2014) showed that the extent of forested wetlands was narrower. In-field assessments of the forested wetlands in the 1990s indicated both transformations and natural rates of growth in different parts of the MCP (Wessels, 1991). However, the increasing suppression of the fire regime in South Africa's Indian Ocean Coastal Belt Biome, is speculated to result in the increased extent of forested wetlands on the MCP. Yet, the trends of this EFG across both the wet and dry years, show a decline. Mangroves, on the other hand, show a decline in extent over the wet years, but are stable during the dry years.

Considering the second hypothesis, that some wetland ecosystem types are more subject to natural hydrological, anthropogenic and/or climate change impacts, remains difficult to prove with certainty. The MCP shows complexity in the combination of hydrological dynamics and anthropogenic and/or climate change impacts. Continuous monitoring using Sentinel-1 and -2, or refinement to PlanetScope at a 3-m spatial resolution, or drone images at certain unimpacted and hotspot areas in relation to both climatic events in anthropogenic interventions (e.g. breaching of estuarine mouth) could hopefully contribute to better monitoring and understanding of changes in the wetland systems.

4.4. Implications for monitoring and global reporting to the Red Listing of Ecosystems, the Global Biodiversity Framework and Sustainable Development Goals

Space-borne satellites such as the Landsat and Sentinel-1 and -2 series of images offer excellent opportunities for monitoring wetland EFGs on the MCP, as part of South Africa's wetland monitoring programs. Expanding these to other areas in the country would require further research and in-field validation, before applying these for palustrine wetland EFGs. New opportunities with the higher spatial resolution of the PlanetScope data at 3 m spatial resolution (Fromm et al., 2025) may also reduce the concerns of commission errors from the Landsat 30 m and Sentinel-1 and -2 at a 10 m spatial resolutions that were evident in this work, when compared to manually mapped extents that was also observed in Van Deventer et al. (2025a) for estuarine habitats of South Africa.

The transformations observed in the wetland EFGs of the MCP have implications for RLE as the first indicator of Target 1 of the GBF, and that may also be used to influence the extent required for restoration under Target 2, and the protection extent required under Target 3. The study identified substantial changes, with 20% of wetlands transitioning to terrestrial classes and an additional 8% shifting to anthropogenic land uses. These rates of change have not been assessed by previous studies on the MCP, nor for the complete extent of the groundwater-dependent ecosystems, and the interconnected aquatic ecosystems on the predominantly groundwater-driven coastal plain. These rates of change indicate that wetland biodiversity in the MCP faces considerable pressures, aligning with GBF Targets 1 and 3, which call for initiative-taking management to reduce biodiversity loss and conserve 30% of critical ecosystems by 2030 (CBD, 2023). Moreover, this study's detailed mapping of wetland EFGs supports SDG 6.6.1, which emphasises the need to track changes in water-related ecosystems over time for reporting at the biome level. Previously, mainly the extent of lacustrine wetlands as the other wetland biome reported to SDG 6.6.1a, was reported, while palustrine wetlands were severely underrepresented (Van Deventer, 2021). Wetlands such as those in the MCP are essential for regional hydrology and biodiversity, and the data provided here offer vital information for SDG 6 monitoring, filling a key gap in wetland representation identified by Van Deventer et al. (2020). Other studies have also highlighted the global concern for losses and changes in forested wetlands (Yoezer et al., 2026). This study illustrates the capabilities of assessment of these changes, using the methods of Apleni et al. (2026).

4.5. Implications for wetland protection in the MCP, South Africa, and globally

The MCP, as an aquifer-dependent system, presents unique conservation challenges. Wetland changes here often have lateral and cascading effects across the ecosystem due to interconnected groundwater flows. The identification of transformation hotspots, such as between Vasi Pan and eManguzi, as well as on and the iMfolozi/uMsunduzi floodplain, reveals areas that should be prioritised for conservation, aligning with the Ramsar Convention and the African Wetlands Strategy, which emphasise local stakeholder engagement and sustainable management practices (Ramsar Convention Secretariat, 2022). The majority of the wetlands are located within the protected areas (71%; Appendix C; Table C1), 14–8% on Tribal land and 10% on private land, based on intersecting the data with ownership integrated by Van Deventer et al. (2025b). Considering the total extent of EFGs that changed to anthropogenic LULC types, a total of 44 km^2 needs to be under restoration by 2030 for reporting to GBF Target 2 (Appendix C; Table C2). More than 50% of these are associated with the loss in extent of Seasonal marshes (52% of Target 2's extent), with the second-largest loss of Large macrophytes (24%). The feasibility of the extents per EFG and land ownership should be considered by ecologists, land owners, and managers, to identify practical and feasible priorities.

The findings here suggest that national policies should support conservation interventions that account for the interconnectedness of MCPs' wetlands, engaging communities to mitigate anthropogenic pressures while enhancing resilience to climate impacts. At the local government level, the South African National Water Act (Act No 34 of 1998) considers timber plantations as stream flow reduction activities and needs to be licensed as water users (RSA, 1998). These results show that there may be an over-allocation of water licences in the aquifer-dependent MCP, which leads to a reduction in the extent of wetland EFGs. Therefore, the Department of Water and Sanitation (DWS), which is responsible for both the monitoring and management of wetlands in the country, should reconsider water resource allocation and licences in the MCP while also assisting in the prioritisation of intervention programs when considering that multiple wetland EFGs are under threat.

5. Conclusion

This study quantified the rates of change in seven wetland EFGs and the lacustrine biome in the MCP across seven epochs: 1990, 2000, 2006, 2014, 2018, 2020 and 2022. The study utilised Landsat data between 1990 and 2014 and, later, a combination of Sentinel-1 and Sentinel-2 images to classify and assess changes in the wetland EFGs. The study revealed that Landsat data and a combination of Sentinel-1 and Sentinel-2 data can monitor changes in wetland EFGs with acceptable accuracies of >70%. The change results revealed that all the wetland EFGs in the MCP exhibited a downward trend, with accelerated losses observed after 2006. The study also revealed that changes in wetland EFGs are driven by a combination of natural changes and human-induced changes. Finally, the study identified between Vasi Pan and eManguzi, KwaMbila and the iMfolozi/uMsunduzi floodplain as the areas with the most anthropogenic changes in the MCP, and these areas should be prioritised. EO with the space-borne Sentinel-1 and -2 images would therefore be a valuable contribution to monitoring changes in the extent of palustrine wetland EFGs for the MCP. The relevance of these methods for quantifying changes in other wetland EFGs in South Africa and the globe remains to be assessed. The availability of the space-borne PlanetScope and Maxar data also offers an opportunity to assess the reduction in commission errors of the wetland EFGs. The methods used in this study provide a globally replicable approach that can be applied to similar wetland types and regions for reporting to SDG 6.6.1 and the GBF's targets 1–3.

CRediT authorship contribution statement

Heidi van Deventer: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Philani Apleni:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis. **Laven Naidoo:** Writing – review & editing, Supervision, Software, Methodology, Investigation, Funding acquisition, Conceptualization. **Philemon Tsele:** Writing – review & editing, Supervision, Software, Resources, Investigation.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used the free version of Grammarly to check and correct the English language. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

Declaration of competing interest

The authors declare no conflicts of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2026.181709.

Data availability

The data can be downloaded from here: https://doi.org/10.71506/csirza.32006340.

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