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Vegetation Map of South Africa, Lesotho and Swaziland 2018: A description of changes since 2006

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Background: The Vegetation Map of South Africa, Lesotho and Swaziland (National Vegetation Map [NVM]) is a fundamental data set that is updated periodically. The National Biodiversity Assessment (NBA) 2018 process provided an opportunity for a more comprehensive revision of the NVM and better alignment between the terrestrial, marine and estuarine ecosystem maps.

Objectives: The aim of this study was to update the NVM 2018 and quantify spatial and classification changes since NVM 2012, and describe the rationale and data sources utilised. We also quantified spatial errors corrected in this version, highlighted progress since NVM 2006, and identified errors and gaps to make recommendations for future revisions.

Method: Edits made to the NVM in ArcMap 10.4 were categorised into the following five groups for analysis: (1) New types, (2) Boundary edits, (3) Realm re-assignment, (4) Removed and replaced vegetation types and (5) Deleted map area. Changes were quantified by category and biome. We used various software platforms to correct and quantify spatial errors since 2006.

Results: Vegetation types were added (n = 47), removed (n = 35) and had boundary edits (n = 107) in NVM 2018, which affected over 5% of the total map area, compared to 2.6% (2012) and 0.5% (2009) for previous versions. Several sources of error were identified and fixed, and prompted the development of standard mapping protocols.

Conclusion: National Vegetation Map 2018 is the most substantial revision of this data set that now fully aligns with maps of all other realms that form part of the NBA. However, parts of the map remain unrefined and provide opportunities for future work.

Keywords: VEGMAP Project; National Vegetation Map; National Biodiversity Assessment; vegetation mapping; vegetation classification.

Introduction

South Africa has been recognised as a global leader in biodiversity assessment, planning and conservation (Balmford 2003). The biodiversity sector adopts a data-driven approach, drawing on the best available science and information, and is continually refining products by iteratively improving input data (Botts et al. 2019). Recognising that it is nearly impossible to comprehensively map all components of biodiversity, practitioners usually rely on a surrogate data set, the most useful of which is a national map of ecosystem types. In South Africa, the National Vegetation Map (NVM) is a spatial model of the historical extent of South Africa's vegetation types and is a key surrogate data set for the terrestrial ecosystem types. Estimating historical extent is essential because it allows a comparison of contemporary extents with those predating widespread anthropogenic activity. Consequently, the NVM is an invaluable resource for managing South Africa's natural landscapes because it provides a baseline data set for undertaking ecosystem threat assessments, informing national and provincial conservation strategies, and quantifying conservation targets (Brown et al. 2013).

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The temporal point of reference for the extent of vegetation types in the NVM is approximately 1750 AD, prior to widespread colonisation. Mucina, Rutherford and Powrie (2006) refer to this concept as mapping potential natural vegetation, defined as a probabilistic state of vegetation in the absence of human influence. Accordingly, in the first version of the NVM produced in 2006, the vegetation communities in heavily degraded parts of the landscape (e.g. mined or flooded landscapes) were reconstructed following international norms (Baldeck et al. 2014). This included modelling the potential vegetation from remnants of existing vegetation, satellite imagery, land types, geology, soils and sometimes climate. These models are generally good proxies for vegetation types, but are rarely reinforced by field-verified data because of the considerable resources required to undertake bottom-up, data-driven approaches across vast landscapes (Mucina et al. 2016). Consequently, many vegetation types were coarsely mapped in 2006.

Although tools for detecting vegetation cover and impacts on vegetation are advancing rapidly (Adamu, Tansey & Ogutu 2018; Baldeck et al. 2014; Xie, Sha & Yu 2008), these tools allow us to grasp only a snapshot of the current extent of vegetation communities and are of limited use for reconstructing the historical extent of vegetation over 250 years ago. Some landscapes in the Fynbos Biome and in high-altitude regions in the Drakensberg still contain significant remnants of past vegetation communities, allowing reconstruction of previous conditions. However, other landscapes like the Nama Karoo were more accessible to humans and have been degraded, making them poor storytellers of the historical extent of local vegetation. Thus, mapping into the past using current data can be complex and requires a suite of surrogate data sets and expert knowledge to approximate the pre-transformation state.

The authors of NVM 2006 acknowledged the need for further refinement of the map and classification, especially where coarse data sets were used to inform the mapped units (Mucina & Rutherford 2006). Therefore, a dedicated programme, the VEGMAP Project, was established to (1) collect plot-based floristic data for the National Vegetation Database (Rutherford, Mucina & Powrie 2012) and (2) liaise with specialists from across the country to use expert knowledge in a long-term effort to periodically update and improve the NVM. Since 2006, the NVM has been updated three times, in 2009, 2012 and 2018. To ensure comparability, the principles of mapping the potential natural vegetation are maintained in updated versions. National Vegetation Map iterations are improved by a growing body of ecological knowledge (e.g. Lötter 2014); field-verified, fine-scale mapping by regional experts (e.g. Holmes & Pugnalin 2016); higher quality imagery (e.g. Desmet et al. 2009) and new mapping equipment such as modern digitising tablets.

Previous versions of the NVM were refined over relatively small areas with data gathered opportunistically from contributors (Dayaram et al. 2017). These refinements mostly occurred in areas with high development pressure (e.g. urban areas) or areas of traditionally high botanical interest (Dayaram et al. 2017). When the NVM was first developed, the largely terrestrial classification also included elements from estuarine, river, wetland and seashore environments that were approximated on the best available information at the time. However, similar to the NVM, more accurate classification systems and maps have been developed for each of these environments.

The NVM 2018 was developed with the National Biodiversity Assessment (NBA) 2018 in mind and specifically aimed to address alignment between the NVM and the other realms (marine, estuarine and inland aquatic environments). Consequently, many of the refinements to NVM 2018 were co-developed with revisions to maps of ecosystem types for the other three realms so that the products could be seamlessly integrated into a single national map.

This article is the second in a series that accompanies updated versions of the NVM (the first being Dayaram et al. 2017) and summarises changes to NVM 2018. The objectives are to outline mapping and classification changes to the latest version of NVM and provide descriptions of new vegetation types; provide a record of rationale and data sources for these changes; highlight progress in error reduction and identify remaining gaps for map refinement and, finally, identify improved processes for scientists to contribute data sets to further refine the NVM.

Methods

Areas refined in National Vegetation Map 2018 and the editing process

Protocols established for proposing changes to the NVM (Dayaram et al. 2017) were followed during the development of NVM 2018. Proposed changes that affected landscape features from other realms were presented to the National Vegetation Map Committee (the strategic and technical advisory committee of the VEGMAP Project), as well as the relevant national committees for the other realms. For example, changes to wetland features in the NVM were presented to the National Vegetation Map Committee, National Inland Aquatic Committee and National Estuary Committee for strategic advice, technical direction and approval. The NVM was edited in ArcMap 10.4 (2016), in conjunction with Google Earth Pro (2017), and data in the attribute table were analysed in Microsoft Excel (2013).

Edits made to the NVM 2018 were clustered into five categories (Table 1):

- New types: where new vegetation types were added to the classification and associated polygons were added to the map
- Boundary edits: where existing terrestrial vegetation type boundaries were edited in the map (including seashore types assigned to both terrestrial and the coastal component of the marine realm)
- Realm re-assignment: where polygons that overlapped with estuarine areas (as defined by the NBA 2018) were

TABLE 1: The five main categories of changes included in the update of the 2018 version of the National Vegetation Map, the rationale for implementing these changes, data sources and methods used for integration with the map.

Change category	Description of changes	Data sources	Approach for implementation in the NVM 2018
(1) New	(1) Two new vegetation types were added in Namaqualand based on new concepts that did not fit existing vegetation types. (2) Although the 2012 NVM units were based on the Subtropical Thicket Ecosystem Project (STEP) vegetation map (Vlok & Euston-Brown 2002; Vlok, Euston-Brown & Cowling 2003), the 2012 NVM combined large floristic, topographic and climatic variation into single vegetation types. All 14 vegetation types in the Albany Thicket Biome were replaced with 44 new types. One Savanna type was also added during this process.	(1) Existing data from contributors. Fine-scale mapping for municipal conservation plans (Desmet at al. 2009). (2) Created from a modification of existing maps. Thicket experts, including original developers of the STEP vegetation map, modified the map for the VEGMAP classification system. This was a re-arrangement of the mosaic and solid thicket types as defined by Vlok and Euston-Brown (2002) and Vlok et al. (2003).	(1–2) Two new vegetation types from Namaqualand were integrated with the rest of the Namaqualand boundary edits using the Update tool. New types from the Thicket Biome were also integrated with the Update tool after slivers and possible gaps were removed.
(2) Boundary edits	(1) The boundaries of many existing vegetation types in the Bushmanland, Namaqualand, West Coast District Municipality and Kamiesberg areas were coarsely mapped in previous versions. (2) Forests in the vegetation map were mapped with the best available knowledge in 2006, but delineations in Mpumalanga, Limpopo and the Eastern Cape contained both commission (including plantation forestry) and omission errors. (3) Isolated patches of a few vegetation types in the City of Cape Town did not match the NVM during field verification. (4) Woodbush Granite Grassland (Gm25) was poorly mapped. This type was closely associated with Forest biome edits in Limpopo. (5) NVM 2012 had topology and edge-matching errors mainly around previously updated areas, for example polygons around the boundary of the City of Cape Town. Polygon nodes may have shifted between the main vegetation map and the shapefile used to update the area. (6) †Seashore vegetation types were coarsely mapped in all previous NVM versions. The coastal edge of the NVM 2012 erroneously delineated parts of the ocean as terrestrial vegetation and under-mapped terrestrial vegetation as ocean because the coarse scale at which the seashore vegetation types were mapped did not allow for accurate mapping of the coastal edge.	(1) Existing maps from fine-scale municipal conservation plans (Desmet et al. 2009). (2) New and existing data. Existing forest polygons from the Mpumalanga Province provincial vegetation map 2014 (Lötter 2014) were used for this province. Forest polygons had been partially refined for the Eastern Cape Biodiversity Conservation Plan (ECBCP 2018) and by some forest experts. No new mapping existed for the Limpopo Province. Therefore, the remaining areas of the Eastern Cape and Limpopo were refined by the VEGMAP team through a focused desktop digitising process. (3) Existing field-verified City of Cape Town fine-scale vegetation map. (4) New mapping. Woodbush Granite Grassland was re-mapped using satellite imagery as a guide. (5) New mapping. Edge-matching was fixed manually. (6) †A coastal expert refined the boundaries of all seashore types at a scale of < 1:3000. Seashore vegetation types were defined using Tinley (1985) Zone II/III break (or equivalent boundary in areas where there was no scrub/thicket) to the dune base and were mapped using satellite imagery (Harris et al. 2019). Historical maps and photographs from the 1800s were used for delineating the historical coastline around harbours (e.g. Cape Town).	(1–4) All existing maps were corrected for topology errors, assigned NVM attributes and incorporated into the NVM 2018 using the Update tool in ArcMap. To prevent overlapping polygons and unnecessary slivers, all NVM 2012 forest polygons in the Eastern Cape and Limpopo were merged into the surrounding non-forest vegetation types and completely replaced by new delineations. (5) GIS errors were fixed by panning around the City of Cape Town boundary and editing polygons manually using imagery as a guide to inform minor polygon adjustments for better alignment. (6) †A mask was created using the dune base boundary of the new coastal features. All features seaward of the dune base line were erased. The new coastal polygons were then added to the NVM with the Update tool, and marked in the cross-realm field as both coastal and terrestrial. Any slivers of old seashore polygons along the inward extent of seashore vegetation types were identified and manually merged into the closest terrestrial type.
(3) Realm re-assignment	During the NBA 2018 process, classification systems and maps of ecosystem types were further refined for each realm. To prevent overlaps and potential inconsistencies with shared features, all vegetation types more appropriately represented in other realm maps were marked as a shared feature in a cross-realm field (e.g. water bodies, vegetation within estuaries or the coastal component of the marine realm). (1) †As part of the NBA process, estuarine experts re-mapped the water and vegetation within all South African estuaries within a zone influenced by estuarine processes called the Estuarine Functional Zone (EFZ) (Veldkornet, Adams & Van Niekerk 2015).	(1) †The EFZ was mapped by estuarine experts and was relatively coarse, including terrestrial vegetation only periodically inundated by flooding. However, where estuarine vegetation was mapped, it was done at a finer scale and with much higher accuracy than the work that had been done for the NVM to date. Therefore, terrestrial vegetation within the EFZ was refined and distinguished from terrestrial vegetation outside the EFZ by an attribute field. The finer-scale estuarine data set was incorporated into the NVM.	(1) †The new EFZs were included in the NVM using the Update tool and initially replaced all vegetation within the EFZ. During this process, some types (e.g. Cape Coastal Lagoons) were removed from the NVM classification. Thereafter pieces of terrestrial vegetation types from 2012 were reinserted within the EFZ, refined, and these polygons were tagged as terrestrial features within the EFZ in the cross-realm field. Data on the non-terrestrial, estuarine vegetation (such as reeds, salt marshes and sedges) within the EFZ were included where available as non-terrestrial vegetation types.
(4) Removed and replaced vegetation types	†During the cross-realm alignment process a careful review by inland aquatic (mainly freshwater) experts and the National Vegetation Map Committee concluded that wetland-related vegetation types and features were describing community-scale types that were not equal to landscape-scale terrestrial vegetation types. Some of these community-scale polygons were also inaccurately mapped and delineated infrastructure such as dams (Van Deventer et al. 2018). Consequently, these types were removed from the vegetation map and classification.	†Inland aquatic-related polygons were identified by name and definition in Mucina et al. (2006). Each polygon was individually inspected using satellite imagery and marked for removal from the map. Only four large water bodies were included (polygons from the National Wetland Map 5) in the NVM as these landscape-scale features reduced the surface area of the surrounding terrestrial vegetation type by 1% – 4%.	†Marked polygons were selected and merged into the surrounding non-wetland vegetation type. Polygons that straddled the boundary of more than one vegetation type were edited manually using the cut tool to divide the polygon between each terrestrial vegetation type. If a unit nested > 70% in a terrestrial unit, the entire aquatic polygon was merged into the unit. If the unit was < 70% in any terrestrial type, the 'cut' tool in ArcMap was used to cut the freshwater unit into segments using satellite imagery. Segments were merged into the closest terrestrial unit.
(5) Deleted map area	Human infrastructure such as ports and reclaimed land were also mapped as part of the historical terrestrial vegetation. These mapping errors created overlaps and gaps with the national marine map of ecosystem types.	Reclaimed land (added in 2009) was removed, as it did not represent the historical extent of vegetation. Other mapped infrastructure such as harbours was also removed.	Erroneous polygons were removed during the refinement of coastal features (see Boundary edits)

Note: Changes influenced by maps from other realms are marked with a (†). Detailed GIS methods are available in technical reports on request from vegmap@sanbi.org.za.
NBA, National Biodiversity Assessment; NVM, National Vegetation Map; GIS, geographic information systems.

refined and served as polygons in the NVM, but were removed from the list of vegetation types in the classification system and do not form part of the terrestrial vegetation units

- Removed and replaced vegetation types: where inland aquatic vegetation types (area was re-assigned to surrounding terrestrial types) and replaced vegetation types in the Albany Thicket Biome were removed from both the terrestrial map and classification system
- Deleted map area: area erroneously mapping reclaimed land or ocean as historical vegetation was deleted from both the map and classification.

The national estuarine, marine and inland aquatic maps of ecosystem types should be used in conjunction with the NVM at locations where the newly added cross-realm field indicates an area of overlap with maps from the other realms.

The vegetation map is a contiguous map of landscape features. Therefore, any change in one part of the map has an influence on adjacent features. Given the numerous changes that were made for the NVM 2018, a clear and sequential protocol was followed to prevent spatial errors. Edits were integrated into the map in the following order: (1) wetlands, water bodies, forests in target areas and estuary types were removed from the map; (2) refined maps in West Coast, Namaqualand, Bushmanland, Kamiesberg areas, the Mpumalanga Province and the Albany Thicket Biome were added; (3) isolated boundary edits (e.g. City of Cape Town) and boundary-edge mismatches were fixed; (4) new forest polygons were incorporated into the map; (5) refined polygons from the estuarine realm and coastal features (marine realm) were incorporated into the map and (6) where appropriate, terrestrial polygons within estuaries were refined and reinstated.

Processes to reduce error in National Vegetation Map 2018

All spatial data were reviewed for topology errors before and after integration into the master version of the NVM by identifying and eliminating gaps and overlaps. All slivers were removed, except for a few narrow polygons close to the boundary between the NVM and Estuarine Functional Zone (EFZ) of the estuarine realm map. Self-intersecting polygons were identified in R version 3.5.1 (R Core Team 2018) using the following packages (code in the Online Appendix, A1): *rgeos* (Bivand & Rundel 2018), *maptools* (Bivand & Lewin-Koh 2017), *rgdal* (Bivand, Keitt & Rowlingson 2018) and *cleango* (Blondel 2017), and removed manually. Several contributors did not have licenses for ArcMap. Hence, data received from or shared with these contributors were in a shapefile format rather than a geodatabase format. When using the shapefile format, a data set may undergo a spatial nudge or 'polygon node creep', causing sliver-sized differences between copies of the map (Cepicky 2017). To reduce spatial shifts and increase stability in the map between working versions, the map was developed and maintained within the more stable geodatabase environment in ArcMap 10.4 and a standard projection (Online Appendix, A1) was used across all realm maps. Within the environment settings of each feature data set, the Z and M coordinate values were disabled, thus further reducing possible error and file size. All edited areas were reviewed by the relevant realm and biome experts before final inclusion in the NVM 2018.

Following a visual comparison of polygons that were unchanged through boundary and classification edits across NVM 2006, 2009, 2012 and 2018, a slight spatial nudge was observed in the shapefile, and boundaries of polygons were not coincident with themselves across data sets. This spatial nudging has been noted by other users of the shapefile format (Cepicky 2017) possibly because of the lack of a compulsory coordinate system definition. Shifting caused by Z and M values in working files of previous versions may have also contributed to the problem. We quantified the area of the NVM affected by spatial nudge from 2006 to 2018 to emphasise the need for protocols that will help reduce the creeping effect produced by shapefiles so that all future versions can be coincident and spatially comparable.

Quantifying changes and errors in National Vegetation Map 2018

After classifying NVM 2018 changes into categories, the NVM 2012 and NVM 2018 feature data sets were combined using the Union tool in ArcMap 10.4. The attribute tables were compared using pivot tables in Microsoft Excel. All rows identical in NVM 2012 and NVM 2018 were removed so that only the polygons that had been changed in 2018 remained. The areas of remaining values were summarised according to the five change categories.

To quantify the total area updated in the NVM since 2006, as well as the area affected by shifting data sets, we combined the 2006 and 2018 feature data sets using the Union tool in ArcMap 10.4. The attribute tables were compared using pivot tables in Microsoft Excel. All rows identical in NVM 2006 and NVM 2018 were removed so that only the pieces of polygons that had been changed in 2018 remained. However, some polygons did not present real spatial or classification changes, but were rather indications of polygon node creep. Therefore, all slivers (from real change and polygon node creep) were identified by calculating 'thinness' (Merchant, Shah & Castleman 2008) using the following formula in the Field Calculator in ArcMap 10.4, where sliver polygons have a ratio close to 0:

T = 4π ([Shape_Area]/([Shape_Length][Shape_Length]))

These polygons were sorted by size, inspected visually and manually separated into those that represented real changes and those that were a result of polygon node creep. Finally, we used Microsoft Excel to calculate total area (percentage) of real change and area affected by polygon node creep from NVM 2006 to NVM 2018.

Ethical consideration

This article followed all ethical standards for research with no collections of plant, animal, or human subjects. Information was gathered from willing contributors and every effort has been made to credit data contributors in the shared data set.

Results

National Vegetation Map 2018

National Vegetation Map 2018: Classification changes since National Vegetation Map 2012

The NVM 2018 had 459 vegetation types. Polygon boundaries were refined for 107 vegetation types, but the area of only 45 of these was changed by more than 10% (Table 2). Forty-seven vegetation types and 13 subtypes were added, mainly from existing maps, initially created for other purposes such as provincial and municipal biodiversity

TABLE 2: Vegetation types affected by changes (i.e. boundary shifts of existing vegetation types, vegetation types and subtypes added, vegetation types removed, and deleted non-vegetated landscape features) in the 2018 version of the National Vegetation Map.

Vegetation type	Proportion of type changed (%)	Vegetation type	Proportion of type changed (%)	Vegetation type	Proportion of type changed (%)
Polygon boundary edits					
Albany Alluvial Vegetation (AZa6)	11	Knersvlakte Shale Vygieveld (SKk4)	43	Northern Afrotemperate Forest (FOz2)	47
Aggeneys Gravel Vygieveld (SKr19)	90	Lower Gariep Alluvial Vegetation (AZa3)	16	Northern Coastal Forest (FOz7)	69
Amathole Montane Grassland (Gd1)	14	Namaqualand Arid Grassland (SKs11)	17	Northern Knersvlakte Vygieveld (SKk1)	24
Bokkeveld Sandstone Fynbos (FFs1)	51	Namaqualand Blomveld (SKn3)	36	Northern Mistbelt Forest (FOz4)	29
Bushmanland Basin Shrubland (NKb6)	17	Namaqualand Granite Renosterveld (FRg1)	64	Northern Richtersveld Yellow Duneveld (SKs2)	15
Bushmanland Inselberg Shrubland (SKr18)	40	Namaqualand Heuweltjieveld (SKn4)	59	Platbakkies Succulent Shrubland (SKn5)	23
Bushmanland Sandy Grassland (NKb4)	34	Namaqualand Inland Duneveld (SKs9)	88	Richtersveld Red Duneveld (SKs5)	12
Central Knersvlakte Vygieveld (SKk2)	43	Namaqualand Klipkoppe Shrubland (SKn1)	14	Richtersveld Sandy Coastal Scorpionstailveld (SKs4)	20
Eastern Gariep Plains Desert (Dg9)	48	Namaqualand Riviere (AZi1)	64	Riethuis-Wallekraal Quartz Vygieveld (SKs10)	57
Garden Route Granite Fynbos (FFg5)	14	Namaqualand Sand Fynbos (FFd1)	31	Scarp Forest (FOz5)	56
Ironwood Dry Forest (FOz9)	70	Namaqualand Shale Shrubland (SKn2)	12	Southern Coastal Forest (FOz6)	46
Kamiesberg Granite Fynbos (FFg1)	63	Namaqualand Spinescent Grassland (SKs12)	19	Southern Mistbelt Forest (FOz3)	98
Kamiesberg Mountains Shrubland (SKn6)	74	Namaqualand Strandveld (SKs7)	21	Vanrhynsdorp Gannabosveld (SKk5)	21
Knersvlakte Dolomite Vygieveld (SKk6)	59	Namib Lichen Fields (Dn2)	52	Western Bushmanland Klipveld (SKt1)	73
Knersvlakte Quartz Vygieveld (SKk3)	28	Nieuwoudtville Shale Renosterveld (FRs2)	17	Woodbush Granite Grassland (Gm25)	30
New vegetation type					
Albany Arid Thicket (AT15)	n/a	Fish Mesic Thicket (AT31)	n/a	Nanaga Savanna Thicket (AT45)	n/a
Albany Bontveld (AT16)	n/a	Fish Valley Thicket (AT32)	n/a	Oudtshoorn Karroid Thicket (AT46)	n/a
Albany Mesic Thicket (AT17)	n/a	Gamka Arid Thicket (AT33)	n/a	Saltaire Karroid Thicket (AT47)	n/a
Albany Valley Thicket (AT18)	n/a	Gamka Valley Thicket (AT34)	n/a	Sardinia Forest Thicket (AT48)	n/a
Baviaans Valley Thicket (AT19)	n/a	Geluk Grassland Thicket (AT35)	n/a	South Eastern Coastal Thornveld (SVs8)	n/a
Bethelsdorp Bontveld (AT20)	n/a	Goukamma Dune Thicket (AT36)	n/a	Southern Namaqualand Quartzite Klipkoppe Shrubland (SKn7)	n/a
Buffels Mesic Thicket (AT21)	n/a	Gouritz Valley Thicket (AT37)	n/a	St Francis Dune Thicket (AT57)	n/a
Buffels Valley Thicket (AT22)	n/a	Grahamstown Grassland Thicket (AT38)	n/a	Sundays Arid Thicket (AT49)	n/a
Crossroads Grassland Thicket (AT23)	n/a	Grassridge Bontveld (AT39)	n/a	Sundays Mesic Thicket (AT50)	n/a
Doubledrift Karroid Thicket (AT24)	n/a	Hamburg Dune Thicket (AT56)	n/a	Sundays Valley Thicket (AT51)	n/a
Eastern Gwarrieveld (AT25)	n/a	Hartenbos Dune Thicket (AT40)	n/a	Thorndale Forest Thicket (AT52)	n/a
Elands Forest Thicket (AT26)	n/a	Kasouga Dune Thicket (AT41)	n/a	Umtiza Forest Thicket (AT53)	n/a
Escarpment Arid Thicket (AT27)	n/a	Koedoeskloof Karroid Thicket (AT42)	n/a	Vanstadens Forest Thicket (AT54)	n/a
Escarpment Mesic Thicket (AT28)	n/a	Mons Ruber Fynbos Thicket (AT43)	n/a	Western Gwarrieveld (AT55)†	n/a
Escarpment Valley Thicket (AT29)	n/a	Motherwell Karroid Thicket (AT44)	n/a	Willowmore Gwarrieveld (AT58)†	n/a
Fish Arid Thicket (AT30)	n/a	Namaqualand Heuweltjie Strandveld (SKs14)	n/a	-	-
Removed and replaced vegetation types					
Albany Coastal Belt (AT9)	100	Eastern Temperate Freshwater Wetlands (AZf3)	100	Namaqualand Salt Pans (AZi2)	100
Albany Dune Strandveld (AZs2)	100	Gamka Thicket (AT2)	100	Northern KwaZulu-Natal Shrubland (Gs5)‡	100
Algoa Dune Strandveld (AZs1)	100	Gamtoos Thicket (AT4)	100	Southern Cape Valley Thicket (AT1)	100
Arid Estuarine Salt Marshes (AZe1)	100	Great Fish Noorsveld (AT10)	100	Southern Kalahari Salt Pans (AZi4)	100
Buffels Thicket (AT12)	100	Great Fish Thicket (AT11)	100	Subtropical Estuarine Salt Marshes (AZe3)	100
Camdebo Escarpment Thicket (AT14)	100	Groot Thicket (AT3)	100	Subtropical Freshwater Wetlands (AZf6)	100
Cape Estuarine Salt Marshes (AZe2)	100	Highveld Salt Pans (AZi10)	100	Subtropical Salt Pans (AZi11)	100
Cape Inland Salt Pans (AZi9)	100	Kowie Thicket (AT8)	100	Sundays Noorsveld (AT5)	100
Cape Vernal Pools (AZf2)	100	KwaZulu-Natal Coastal Belt (CB3)‡	100	Sundays Thicket (AT6)	100
Coega Bontveld (AT7)	100	Lesotho Mires (AZf5)	100	Cape Lowland Freshwater Wetlands (AZf1)	100
Drakensberg Wetlands (AZf4)	100	Lower Karoo Gwarrieveld (NKl3)	100	Western Gwarrieveld (SKv9)†	100
Eastern Cape Escarpment Thicket (AT13)	100	Lydenburg Montane Grassland (Gm18)‡	100	Willowmore Gwarrieveld (SKv12)†	100
Removed non-vegetated landscape features					
Cape Coastal Lagoons (W3)	100	Reclaimed land (W5)	100	Subtropical Coastal Lagoons (W2)	100
Freshwater Lakes (W1)	100	-	-	-	-
New subtypes					
Cape Seashore Island Vegetation (subtype of Cape Seashore Vegetation) (AZd3.2)	n/a	Bushmanland Inselberg Succulent Shrubland (subtype of Namaqualand Klipkoppe Shrubland) (SKn1.2)	n/a	Waterford Doringveld (subtype of Sundays Arid Thicket) (AT49.2)	n/a
Groot Gwarrieveld (subtype of Eastern Gwarrieveld) (AT25.1)	n/a	Namaqualand Calcrete Pans (subtype of Namaqualand Sand Fynbos) (FFd1.2)	n/a	Barandas Gwarrieveld (subtype of Willowmore Gwarrieveld) (AT58.2)	n/a
Kleinpoort Karroid Thicket (subtype of Eastern Gwarrieveld) (AT25.2)	n/a	Saldanha Granite Island Strandveld (subtype of Saldanha Granite Strandveld) (FS2.2)	n/a	Gamtoos Gwarrieveld (subtype of Willowmore Gwarrieveld) (AT58.3)	n/a
Sundays Gwarrieveld (subtype of Eastern Gwarrieveld) (AT25.3)	n/a	Sundays Arid Thicket (subtype of Sundays Arid Thicket) (AT49.1)	n/a	Willowmore Gwarrieveld (subtype of Willowmore Gwarrieveld) (AT58.1)	n/a
Langebaan Dune Island Strandveld (subtype of Langebaan Dune Strandveld) (FS5.2)	n/a	-	-	-	-

Note: The percentage of the type that was affected by changes is indicated where relevant. n/a, not applicable.

†, Names present in previous versions have been revised and are now new vegetation types with new codes, delineations and definitions.

‡, Removed in the 2012 version and not recorded in Dayaram et al. (2017). New vegetation types are described in Online Appendix, Table 1.

conservation planning. The names of two Albany Thicket types were retained from 2012, but the descriptions were completely revised. These types were thus classified as new. The number of Azonal vegetation types reduced by 16 vegetation types from 34 to 18 vegetation types as a result of the removal of freshwater-related systems and the re-assignment of estuarine-related vegetation types. Azonal vegetation types retained in the classification represented large alluvial landscape units. All four water body classes were deleted from the classification either by deletion (i.e. Reclaimed Land) or replacement by the EFZ (i.e. Cape Coastal Lagoons, Freshwater Lakes and Subtropical Coastal Lagoons).

The number of vegetation types in the Albany Thicket Biome increased from 14 to 44. Savanna vegetation types increased by one type to 91. The number of vegetation types in the Desert (*n* = 15), Forests (*n* = 12), Grasslands (*n* = 74), Indian Ocean Coastal Belt (*n* = 6) and Fynbos (*n* = 122) biomes remained unchanged. The Succulent Karoo lost and gained two vegetation types (*n* = 64). Western Gwarrieveld (SKv9) and Willowmore Gwarrieveld (SKv12) were removed from the classification under the Succulent Karoo Biome. These names were recycled with the definitions of new types added in the Albany Thicket Biome. The Nama Karoo (*n* = 13) lost one vegetation type, NKI3 Lower Karoo Gwarrieveld, which was absorbed into new vegetation types in the Albany Thicket Biome. This change was a consequence of the refinement of the Albany Thicket Biome and not targeted at refining the Nama Karoo Biome.

National Vegetation Map 2018: Spatial changes since National Vegetation Map 2012

Changes to NVM 2018 affected a total of 5.72% (72 499 km^2) of the current map area. Only 0.01% of the 2012 map area was deleted during the refinement of the coastal edge for NVM 2018 (Figure 1). New vegetation types added to the NVM 2018 classification constituted the largest proportion of the area changed (59.9%). Edits to the boundaries of existing vegetation types contributed to 39.3%; the re-assignment of vegetation types to the estuarine realm contributed to 0.6% and the removal of vegetation types associated with inland aquatic systems contributed to 0.2% of the total map area.

Most changes (45%) to the area of NVM 2018 were in the Albany Thicket Biome, primarily because of the addition of 44 new vegetation types. Most edits in the Succulent Karoo Biome (16.74% of total area) and Nama Karoo Biome (15.40% of total area) were from boundary edits of existing types (13.96% and 14.28%, respectively). Grasslands accounted for 5.70% of the total area of changes (of which 4.23% was because of removed wetland vegetation types from the Azonal vegetation group). Changes in the Savanna Biome contributed to 5.45% (of which 2.31% was because of the addition of a new type); Forests to 3.48% (of which 3.35% was because of boundary edits and 0.13 was because of small areas removed during cross-realm refinements); Azonal vegetation to 2.91% (of which 2.15 % were boundary edits); Fynbos to 2.85% (with 2.21% boundary edits); Desert to 1.02% (of which 1.01% were predominantly boundary edits) and Indian Ocean Coastal Belt to 0.60%, with changes divided between boundary edits (0.21%) and removed wetland type polygons (0.28%) of the total changes.

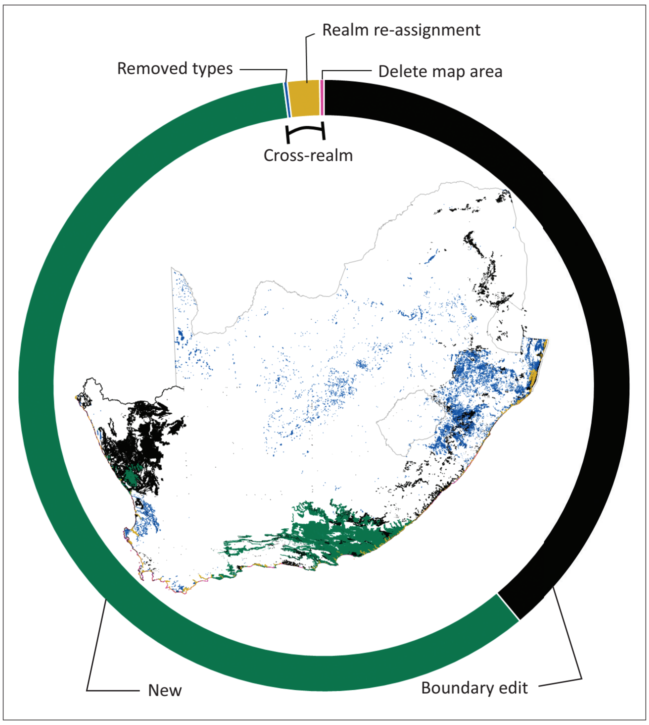

FIGURE 1: Distribution of the five categories of changes and proportion contributed by each category to the cumulative area changed in the National Vegetation Map 2018, with an indication of which changes affected multiple realms. Only the area affected by removed aquatic vegetation types is shown. These polygons are small and have been slightly emphasised in bold so that they are visible in the figure. The position of Albany Thicket vegetation types that were replaced by new vegetation types has not been shown as these two categories overlap. Refer to Table 1 for details of the change categories.

National Vegetation Map 2018: Changes to the attribute table since National Vegetation Map 2012

New fields were added to the vegetation map (Online Appendix, Table 2) including a 'Cross-realm reference' field, which indicates whether a polygon is also nested within another realm. For example, seashore types generally occur within both the terrestrial realm and coastal component of the marine realm; portions of vegetation types sometimes overlap with the ecosystem types (in the EFZs) of the estuarine realm. Furthermore, a field was added indicating the contributor of the polygon and the source of data used to inform the mapping of a unit.

Improvements since 2006

National Vegetation Map 2006 to 2018: Separating real edits from errors

Since NVM 2006, some 8.83% (2009: 0.5%; 2012: 2.6%; 2018: 5.72%) of the total map area (Figure 2) has been updated. These changes have not overlapped over successive versions and have occurred mainly in Grasslands and Savannas in KwaZulu-Natal, the Albany Thicket, Forests, the Succulent Karoo, and parts of the Nama Karoo and Fynbos. Apart from the removal of inland aquatic features, which affected almost all vegetation types, the central interior of the NVM has not yet been refined. Polygon 'node creep' errors from 2006 to 2018 contributed to only 0.2% of the actual map area. While the overall percentage of errors was small, these errors occurred as very small slivers throughout the map.

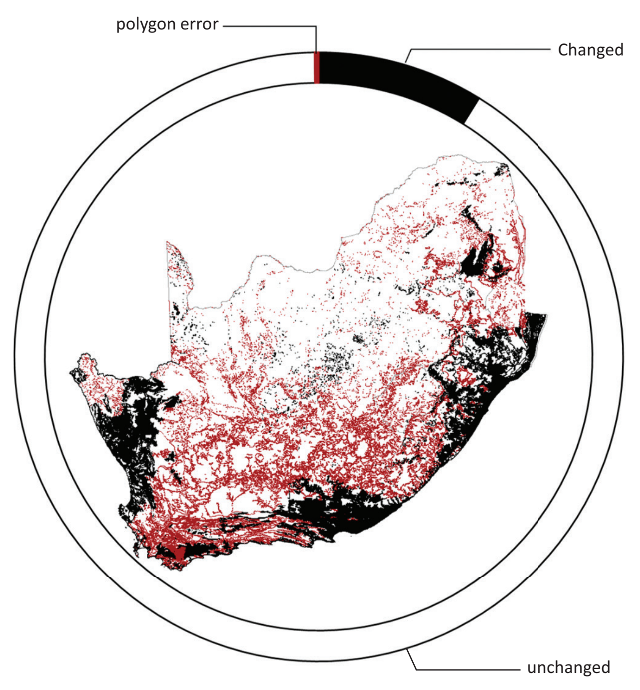

FIGURE 2: Overview of the changes to the area (%) of the National Vegetation Map from 2006 to 2018 showing the area that is unchanged (clear), edited for change (black) and corrected for node creep error (red and in bold to increase visibility of narrow polygons).

Higher densities of 'node creep' were found near areas of real changes where fine-scale maps were received in a shapefile format, for example, NVM 2012 edits in the KwaZulu-Natal Province.

Beyond National Vegetation Map 2018: Data sources and contributors, and targeting future updates

About 40% of the NVM 2018 still has its origins in coarsely mapped land types (Figure 3), represented by a few large polygons across the central and northern parts of South Africa. Polygons derived from modelled abiotic variables contributed to a further 11% of the map area. Together, these polygons overlap with much of the Nama Karoo Biome and a portion of the Grassland Biome. Unsurprisingly, the areas still delineated by land type boundaries and modelled abiotic variables overlap somewhat with the areas that have not yet been refined in NVM updates. Finer-scale polygons with some field verification and those digitised from satellite imagery are higher in number but contribute to a proportionally smaller area of the map. Very few polygons covering a small area, mainly in the Mpumalanga Grasslands, are currently defined on floristic data.

Nineteen contributors provided spatial data and new vegetation type descriptions for the NVM 2018. Most of the area mapped from 2006 to 2018 (54%) has been produced through mixed collaborations (several partners from different organisations were assembled to refine the map and classification in an area), and from conservation planners, botanists and ecologists in private industry (36%). Other contributions were from provincial government (5%),

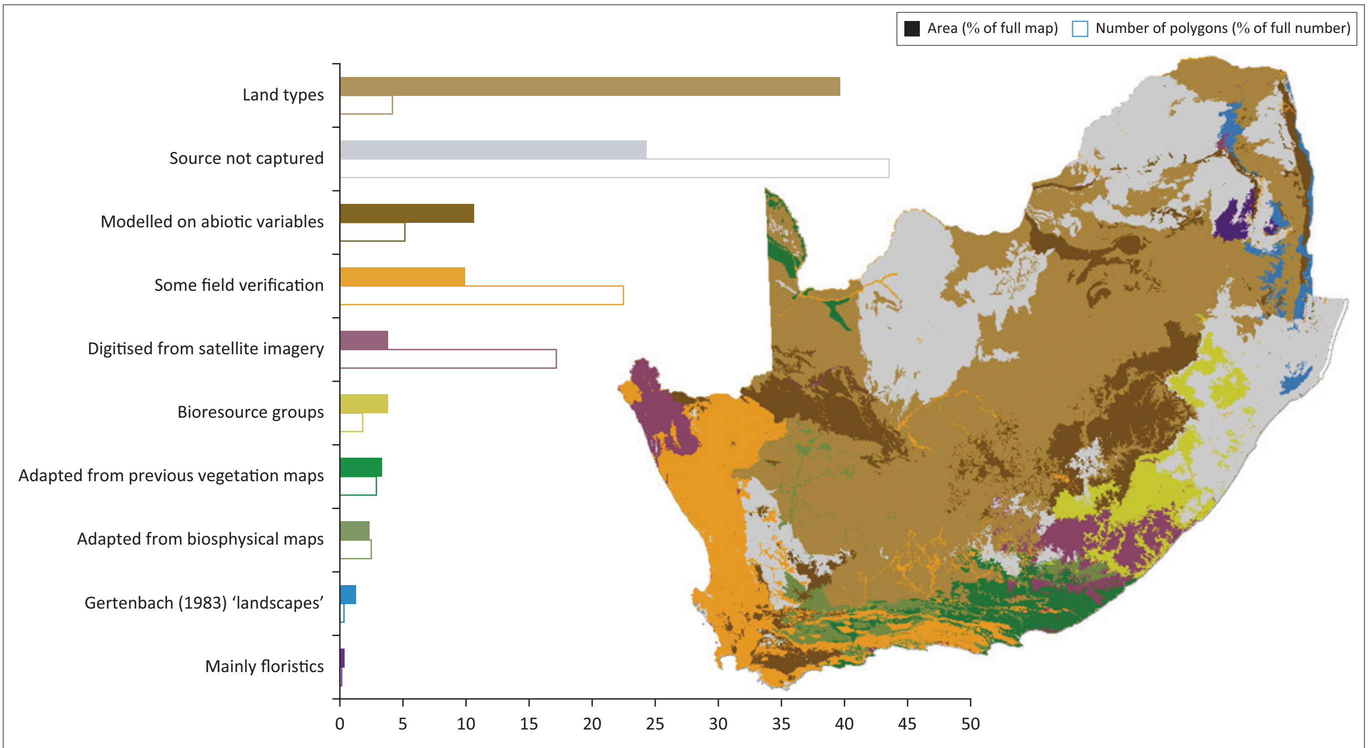

FIGURE 3: Sources of data that informed the mapping of vegetation types from 2006 to 2018 are shown. The percentage area influenced by a data source (as a proportion of the total area of the National Vegetation Map to date) is shown in solid, coloured bars. The percentage of polygons affected by that data source is shown in clear bars with coloured outlines. 'Not captured' indicates vegetation types for which the 2006 data source could not be identified.

parastatal organisations such as the South African National Biodiversity Institute (SANBI) and the Council of Scientific and Industrial Research (CSIR) (3%), universities (0.23%) and municipal government, like eThekwini Municipality (0.03%). The dominance by the first two contributor types provides an indication of our reliance on non-state collaborators.

Discussion

Improvements in mapping

Mapping and classification edits made to the NVM in 2018 had a larger effect than edits from previous years. The map area affected by changes was 1.8 times larger than the 2012 update and NVM 2018 had more types added and removed compared to previous versions. Notable areas updated included coarsely mapped portions of the arid west coast and coarsely classified Albany Thicket vegetation types, both of which were identified as important areas for refinement in the previous map (Dayaram et al. 2017).

Although changes to the NVM 2018 span a much larger area of the map than previous revisions, much of the influence on the number of vegetation types affected by boundary refinements are the result of the removal of Azonal wetland types. Most areas refined since 2006 are within 300 km of the coast, and the interior expanse of the country (a few large polygons sourced from coarse, unverified data sets such as land types) remains unrefined. Ideally, a greater proportion of these unrefined polygons should be supported by field verification, with the map and classification adjusted accordingly.

There was a large difference in the magnitude of edits in NVM 2018, from sliver-sized edits along the coast to alterations of a whole biome in the Albany Thicket. However, the significance of edits does not necessarily diminish with size. Minor changes to boundaries of vegetation types such as Cape Flats Sand Fynbos (0.08% change in area because of a boundary shift) in the City of Cape Town municipality may have a negligible effect on national assessments, but will have important implications for local Environmental Impact Assessments and biodiversity plans. In contrast, major changes to the Albany Thicket Biome (> 90% of the area affected by the introduction of new types) will have a significant impact on statistics and conservation planning at all scales, including national and provincial levels.

This is the first update of the NVM that was explicitly developed for inclusion in an NBA. Previous versions were used in the NBA, but those had been developed prior to, and independent of, the NBA. Consequently, there were mismatches between the NVM 'vegetation types' and the NBA 'ecosystem types', which were assessed in the NBA 2011 (Driver et al. 2012). In the 2018 NBA, 458 vegetation types described in the NVM 2018 (the 459th type lies in Lesotho) were synonymous with the 458 terrestrial ecosystem types included in the assessment, ensuring that the latter are underpinned by the rigour of peer-review inherent in the vegetation mapping process. Alignment with the NBA provided the VEGMAP Project access to previously unavailable resources, such as specialised digitising tablets. Furthermmore, collaborative agreements under the NBA facilitated access to experts who provided vital input for cross-realm vegetation types (e.g. seashore and aquatic types). The NBA also provided a framework for a co-ordinated and targeted strategy to address some previously poorly mapped areas (e.g. forests in the Limpopo and Eastern Cape provinces) in the NVM 2018.

New tools for mapping and identifying errors in the geographic information systems (GIS) mapping environment and hardware that are more sophisticated increased our ability to identify and reduce errors, including removing topology errors, slivers and self-intersects. The geodatabase format allowed us to work within a stable file structure between versions. However, these tools are currently available only from closed-source platforms, creating constraints and limiting the quality of data from potential data contributors. Consequently, misalignments may occur between edited parts of the map created in other platforms such as R and Quantum GIS. Misalignments can be minimised if contributors work in the geodatabase version of the file or, if that is not possible, with a file supplied by the NVM custodians so that data sets are only one export away from the latest working data set.

Future contributions are likely to emerge from a pool of experts with diverse affiliations from around South Africa. To date, most of the map has been developed by mixed collaborations (most of these during the development of the NVM 2006, as described in Mucina and Rutherford 2006), demonstrating the importance of collaborative work in this project. Private individuals, including researchers and consultants who volunteered their data, produced because of processes such as conservation planning and Environmental Impact Assessments, were the next largest group of contributors. These individuals have been the main contributors of data in refined versions of the NVM. Contributors from provincial and municipal government, parastatal organisations and universities have also made small but important contributions to improvements in the map. The new 'Contributors' field in the spatial layer is an attempt to acknowledge these efforts, and to encourage further contributions. Collecting data through a network of willing volunteer contributors poses a risk to the long-term sustainability of the NVM refinement. There is also great risk in assuming that remaining coarse areas of the map will be updated in this manner especially as no known contributors currently work in many of these poorly mapped regions. A more targeted approach to refine the mapping and classification in these areas will need to be developed and funding will have to be sourced. While some individuals at private and public institutions collect data using protocols that align with the NVM, many more institutions collect data that cannot be incorporated, precluding map refinement in the areas in which they work. Modifying these collections to fit a national standard for NVM data collection will fast track the finer-scale bottom-up gathering of data, with the ultimate goal of achieving a more robust, stable data-driven baseline map of vegetation across the country.

Given new data formats, the increase in the number of vegetation types and higher resolution of map polygons now poses less of a problem to map display and data storage. Most users currently use an electronic version of the map, which poses fewer limitations on size as geodatabases allow larger file sizes to be stored in a more stable format. The trend towards higher resolution and accuracy in foundational maps provides the opportunity for more accurate assessments of terrestrial ecosystem types under the NBA, better spatial prioritisation of terrestrial biodiversity, more powerful tools for land-use decision-making and, ultimately, improved conservation.

A focus on terrestrial vegetation

Focussing on terrestrial vegetation types in the classification minimises the disjunction that previously existed between the dissimilar scales of units in the map. For example, wetland communities are no longer reflected as equal in scale to an assemblage of communities in a vegetation type. The shift from including estuarine and other aquatic features to a greater focus on terrestrial landscape units in NVM 2018 has also led to more accurate mapping and less conflict between maps used in cross-realm ecosystem assessments. The inland aquatic, estuarine and coastal vegetation units have been mapped by experts in each of those fields, making their delineation superior to previously coarsely mapped units from these realms. Inland wetlands, in particular, are an area of ongoing mapping and revision. Recent work on the classification of inland wetlands suggests that these units are best classified under a more appropriate realm-specific classification system (Sieben 2019). Further mapping and classification by experts will be done in conjunction with the VEGMAP Project team so that units from these realms can remain comparable or nested within the NVM hierarchical system (e.g. the national wetland classification system with more accurate mapping could be nested at the community level in the NVM).

Lessons learned for future versions

The value of updating national-scale vegetation maps and classifications is recognised globally by the Vegetation Classification Working Group of the International Association of Vegetation Science (De Cáceres et al. 2015). As such, efforts to refine the NVM are ongoing under the VEGMAP Project at SANBI. All potential contributors to future versions of the NVM should request or download the latest working version (available on request from vegmap@sanbi.org.za), use the same projection and work as far as possible within the same geodatabase as the latest version of the NVM. Geodatabases provide the opportunity to work within a topology, reduce file size and reduce the potential for error; however, we acknowledge that this is not always possible because of current constraints on access to geodatabase technology. Consequently, polygon node creep in the feature data set may become unavoidable when data received from contributors have been created using another version of the NVM as a base, or if shapefiles have been used to create a contribution. Resultant slight non-real mismatches will have to be resolved with the contributor before assimilation into the master data set.

Conclusion

The vegetation of South Africa is changing rapidly through both anthropogenic development and natural transitions to novel states. This poses a challenge to refine the historical extent of the country's vegetation to improve our understanding of the baseline against which to compare assessments and monitoring. While the map has been refined through three subsequent iterations, provinces such as the North West, Gauteng and Free State, and the Nama Karoo Biome have had no focused updates since 2006. Therefore, a co-ordinated and targeted effort is needed across partner institutions to continue to refine the NVM, especially in South Africa's interior where the original coarsely mapped polygons remain. Refinements emerge from a combination of expert approaches and field surveys to verify vegetation types that fill current gaps in the National Vegetation Database which serves as a powerful complementary tool to the NVM. Nevertheless, the NVM 2018 is South Africa's most up-to-date map of terrestrial vegetation types, and for the first time, aligns seamlessly with the ecosystem type maps of the inland aquatic, estuarine and marine realms.

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Competing interests

The authors have declared that no competing interests exist.

Authors' contributions

A.D. prepared the draft, provided conceptual input, integrated all changes from contributors into the map and made technical map changes to the coastal edge, wetlands, estuaries, forests and minor edits in other biomes. L.R.H. made major contributions to the mapping and conceptual thinking for seashore vegetation types, as well as contributions to the structure of the manuscript. B.A.G., J.H.J.V. and P.G.D. provided conceptual and technical direction for changes in the Albany Thicket Biome and Arid regions and wrote the descriptions for new vegetation types together with S.v.d.M. A.G.R. contributed to strategic decisions and map edits in the City of Cape Town. L.W.P. assisted with mapping decisions. M.Q. and K.M.H. contributed to technical changes for the Eastern Cape forests. A.L.S. assisted with strategic mapping decisions and with direction of the article. All authors contributed to reviewing and editing the article.

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Data availability statement

The National Vegetation Map 2018 spatial data set and decriptions of new vegetation types can be accessed online from: http://bgis.sanbi.org/Projects/Detail/208

Disclaimer

The authors declare that the views expressed in this article are their own and not an official position of the South African National Biodiversity Institute, Nelson Mandela University, University of the Witwatersrand or the University of Cape Town.

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