A NEW MAP OF STANDARDIZED TERRESTRIAL ECOSYSTEMS OF AFRICA

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A New Map of Standardized Terrestrial Ecosystems of Africa

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The authors represent 37 experts from 18 countries who collaborated to produce the maps and ecosystems classification contained herein. Every author made a significant intellectual, data, and/or analytical support contribution to the work, in addition to participating in the development and review of the document. The invited African ecosystem scientists and vegetation geographers were knowledgeable about the types and distributions of vegetation in their countries and frequently across larger regions, and shared maps and data on the locations of ecosystems. Their dedication to this work, which they perceived as a welcome attempt to unify thinking about African ecosystems and vegetation across the entire continent, was moving, and is much appreciated.

This booklet is published by the Association of American Geographers as a special supplement to the *African Geographical Review*.

A New Map of Standardized Terrestrial Ecosystems of Africa

Abstract

Terrestrial ecosystems and vegetation of Africa were classified and mapped as part of a larger effort and global protocol (GEOSS – the Global Earth Observation System of Systems), which includes an activity to map terrestrial ecosystems of the earth in a standardized, robust, and practical manner, and at the finest possible spatial resolution. To model the potential distribution of ecosystems, new continental datasets for several key physical environment datalayers (including coastline, landforms, surficial lithology, and bioclimates) were developed at spatial and classification resolutions finer than existing similar datalayers. A hierarchical vegetation classification was developed by African ecosystem scientists and vegetation geographers, who also provided sample locations of the newly classified vegetation units. The vegetation types and ecosystems were then mapped across the continent using a classification and regression tree (CART) inductive model, which predicted the potential distribution of vegetation types from a suite of biophysical environmental attributes including bioclimate region, biogeographic region, surficial lithology, landform, elevation and land cover. Multi-scale ecosystems were classified and mapped in an increasingly detailed hierarchical framework using vegetation-based concepts of class, subclass, formation, division, and macrogroup levels. The finest vegetation units (macrogroups) classified and mapped in this effort are defined using diagnostic plant species and diagnostic growth forms that reflect biogeographic differences in composition and sub-continental to regional differences in mesoclimate, geology, substrates, hydrology, and disturbance regimes (FGDC, 2008). The macrogroups are regarded as meso-scale (100s to 10,000s of hectares) ecosystems. A total of 126 macrogroup types were mapped, each with multiple, repeating occurrences on the landscape. The modeling effort was implemented at a base spatial resolution of 90 m. In addition to creating several rich, new continent-wide biophysical datalayers describing African vegetation and ecosystems, our intention was to explore feasible approaches to rapidly moving this type of standardized, continent-wide, ecosystem classification and mapping effort forward.

In 2005, a consortium of nations, the Group on Earth Observations (GEO), convened and created the Global Earth Observation System of Systems (GEOSS). GEOSS is an intergovernmental protocol aimed at promoting and facilitating the use of earth observations, both in-situ and remotely-sensed, for societal benefit. GEOSS is programmatically organized into nine societal benefit areas (ecosystems, biodiversity, weather, disasters, health, water, energy, climate, and agriculture). The ecosystems societal benefit area includes a task (EC-01-C1) to develop a standardized, robust, and practical classification and map of global ecosystems (Sayre et al., 2007). This task is currently described in the GEOSS 2012-2015 work plan.[1] It was originally commissioned in the initial framework GEOSS ten year work plan.[2] The methodology for producing these standardized terrestrial ecosystems has previously been implemented for South America (Sayre et al., 2008) and the United States (Sayre et al., 2009) and was adapted for Africa as described below.

Numerous ecological regionalizations of Africa exist. Notable among them are the biogeographical provinces of Udvardy (1975), the pioneering work of Frank White (1983) to map phytochorological regions (based on the number of endemic species), the phytogeographic maps (floristic regions) of Takhtajan (1986), and more recently the terrestrial ecoregions of Bailey (1998) and the World Wildlife Fund (Burgess et al., 2004). These interpretive efforts, drawing extensively upon expert knowledge and intuitive boundary demarcation, have considerably advanced the understanding of African ecogeography. A potential vegetation map extending White's (1983) chorological emphasis in greater detail across seven east African countries has been produced as part of a seven volume monograph series and atlas (Lillesø et al., 2011). Remote sensing-derived maps of regional and global land cover such as those from the Africover (FAO, 1997), Global Land Cover 2000 (Mayaux et al., 2006) and the GlobCover 2005 (Bicheron at al., 2006) products have similarly provided increasingly quantitative and finer spatial resolution characterizations of vegetation cover for

Africa. The work described herein represents a new effort to model African ecosystem distributions across the entire continent at a 90m base resolution using physical environment data and geospatial statistics.

Modeling Approach

Terrestrial vegetation occurs in response to the physical characteristics of the environment, evolutionary and biogeographic history, and historical manipulation of land by humans. We define a local scale terrestrial ecosystem as an area characterized by spatially co-occurring vegetation assemblages that share a common ecological gradient, substrate, or process (Comer et al., 2003). The GEOSS approach to modeling ecosystems is to map the biophysical settings across landscapes, and then associate described vegetation types to those unique biophysical areas. A vegetation classification is used as a set of *a priori* concepts to provide labels that will be associated with the physical environments for spatial modeling (i.e. a map product). Previous GEOSS-related terrestrial ecosystem modeling efforts for South America (Sayre et al., 2008) and the conterminous United States (Sayre et al., 2009) relied heavily on existing detailed vegetation classifications and expert-derived, attribution-based "rulesets" to accomplish the labeling step. In Africa, however, a continent-wide, detailed, fine thematic resolution vegetation classification reflecting major vegetation composition was lacking, and was therefore specifically developed for this effort. Thirty seven experts from eighteen countries developed the classification as a rich and comprehensive multi-level hierarchical list and description of African vegetation types. Subsequently, these experts provided thousands of field-based sample locations where these vegetation types were known to occur. The sample locations were then used as input data to the inductive modeling, which was accomplished using a classification and regression tree (CART) approach (Breiman et al., 1984).

The classification and regression tree approach is a data mining method to identify explanatory patterns between field samples and mapped environmental datalayers. The mapped layers may describe either categorical or continuous variables, and relating them to the response variable has been shown to be a powerful technique for ecological analysis and habitat mapping (De'ath and Fabricus, 2000; Lowry et al., 2007). The model analyzes the suite of biophysical parameters (including elevation, landforms, lithology, bioclimate, and regional phytogeography) at each sample location of a vegetation type, and then constructs a regression relationship between the independent environmental predictor variables and the dependent variable, the labeled vegetation type sample. The model then recursively partitions all space into a "most probable vegetation type" for each pixel. The CART software used is the See5™ (RuleQuest Research) program, which iterates each model run ten times (boosting function of ten). Each successive iteration removes model relationships with the lowest predictive power.

The resulting map depicts the potential distribution of all ecosystem types, representing the probable distribution relative to major 'natural' explanatory variables, and in the absence of human disturbance. Many of the mapped locations of ecosystems will have been converted to development or agriculture. A map of current ecosystems and land use/land cover could be derived from the potential ecosystems map with the inclusion of additional information on human-altered landscapes; however, mapping current ecosystem distributions was outside the scope of this effort.

Vegetation Classification

The draft African vegetation classification that was produced[3] (Appendix) is preliminary, but builds on existing work (e.g. Mucina and Rutherford, 2006) and should be considered as a starting point to a more robust hierarchical vegetation classification and description for Africa. The classification could be improved with the addition of new vegetation units (including sample locations) and detailed descriptions at each level of the proposed hierarchy.

The criteria used for vegetation classification are the basis of the United States National Vegetation Classification (FGDC 2008) (http://www.esa.org/vegweb/). The classification logic distinguishes different vegetation types based on five criteria: dominant growth forms, diagnostic growth forms, dominant species, diagnostic species, and compositional similarity (FGDC 2008; Mueller-Dombois and Ellenberg, 1974). Physiognomic and structural criteria include (1) Diagnostic combinations of growth forms; (2) Ecological patterns of either dominant growth forms or combinations of growth forms (growth forms of similar ecological (habitat) and dynamic significance, or growth forms of similar geographical distribution), and (3) Vertical stratification (layering) of growth forms (complexity in structure as produced by arrangement of growth forms). Floristic criteria include (1) Diagnostic combinations of species (differential and character species, constant species, dominant species), (2) Ecological combinations of species (indicator species of similar ecological (habitat) and/or dynamic significance, species of similar geographical distribution), and (3) Vertical stratification (layering) of species (species patterns found in the dominant growth forms or strata, species patterns found between strata (overstory/understory). Classification units were also established to describe the very sparsely vegetated (and predominantly unvegetated) desert landscapes, in order to provide a comprehensive, ecologically-based map legend.

Biophysical Settings – Landforms, Lithology, and Bioclimates

To characterize the general biophysical settings which give rise to and contextualize the vegetation types, we developed raster surface models of landforms, lithology, and bioclimate for the entire continent. These datalayers were subsequently used as the explanatory variables in the CART analysis.

Landforms - We used the 90 m NASA/NGA shuttle radar topographic mission (SRTM) digital elevation model as source data for the characterization of regional physiography in seven landform classes (Figure 1). The landform mapping methodology (modified from True, 2002) was based on an analysis of slope and local relief, and is described in Sayre et al., 2009. Local relief was calculated over a 1 km^2 cell moving window. Slope was classified as gently sloping or not gently sloping using a threshold value of 8%. Local relief is classified into five classes (0-15m, 16-30m, 31-90m, 91-150m, and >150m). Slope classes and relief classes were subsequently combined to produce seven land surface form classes (smooth plains, irregular plains, escarpments, hills, breaks/foothills, low mountains, and high mountains/deep canyons).

Lithology – Substrate type is an important determinant of vegetation distribution (Kruckeberg, 2002). To create a continental map of surficial lithology (Figure 2), we compiled information from existing characterizations of geology and rock type at continental, regional, and national scales. The African surficial lithology map is a compilation and reclassification of twelve geology, soil and lithology databases derived from global (Geologic Data Systems, 2008), regional (FAO et al., 2009) and national (FAO, 2003; DuPuy and Moat, 1998) sources.[4]

All units from these data sources were compiled and reclassified into one of nine bedrock types (carbonate, karst, non-carbonate sedimentary, metasedimentary, alkaline intrusive volcanic, acidic intrusive volcanic, metamorphic intrusive, ultramafic, extrusive volcanic) or one of ten unconsolidated surficial materials (colluvium, hydric organics, aeolian sediments, alluvial fan, fluvial sediments, alluvial beach or dune, alluvial saline, alluvial gypsum, other alluvial, and volcanic ash, tuffs, and mudflows). It is recognized that lithological variation within surface depositional types is possible, but the data did not permit further differentiation of lithological substrate.

Bioclimates - To characterize African bioclimate regions (Figure 3), we used 1 km spatial resolution temperature and precipitation data from the global WorldClim dataset (Hijmans, et al., 2005) and the global bioclimatology model developed by Rivas-Martinez (Rivas-Martinez and Rivas y Saenz, 2007) to map 29 isobioclimates. These isobioclimate regions are areas of relatively homogenous temperature and precipitation regimes, and were constructed from a thermotypes layer (Figure 4) and an ombrotypes layer (Figure 5). Thermotypic regions are areas with a relatively homogenous temperature regime, and ombrotypic regions are areas of relatively homogenous precipitation regime (Rivas-Martinez and Rivas y Saenz, 2007).

All physical environment datalayers were resampled to a 90 m base resolution and reconciled to a new, 90 m African coastline raster datalayer developed specifically for this effort. The coastline dataset was originally developed as a raster dataset at a 30 m spatial resolution, which was subsequently generalized to 90 m. It was created by acquiring the most recent and cloud free Landsat images from the coastline of the entire study area. A total of 435 Landsat images were obtained for analysis. The coastline extraction modeling was implemented using image processing software. The extraction process uses analyst-supplied threshold criteria for interpretation of coastlines, rivers, and estuaries based on visual interpretation. During the coastline tracing routine, river widths were "jumped" at a visual threshold value of approximately 2-3 pixels (60-90 meters). The 30 m Africa coastline datalayer (in both raster and vector formats) is likely the most detailed, highest resolution shoreline datalayer yet developed. It is presented in Figure 6, with an inset graphic depicting the extraction of coastline from a Landsat image.

A Note About the Maps

The continent-wide maps were developed with standard ESRI data on country boundaries. These boundaries should only be interpreted as illustrative, and are not to be construed as legally descriptive in any sense. Moreover, the mapping of the input layers was in an advanced state prior to the emergence of South Sudan as an independent nation, and do not therefore depict South Sudan. The final ecosystems map, however, does depict both Sudanese nations.

Figure 1 - Landforms

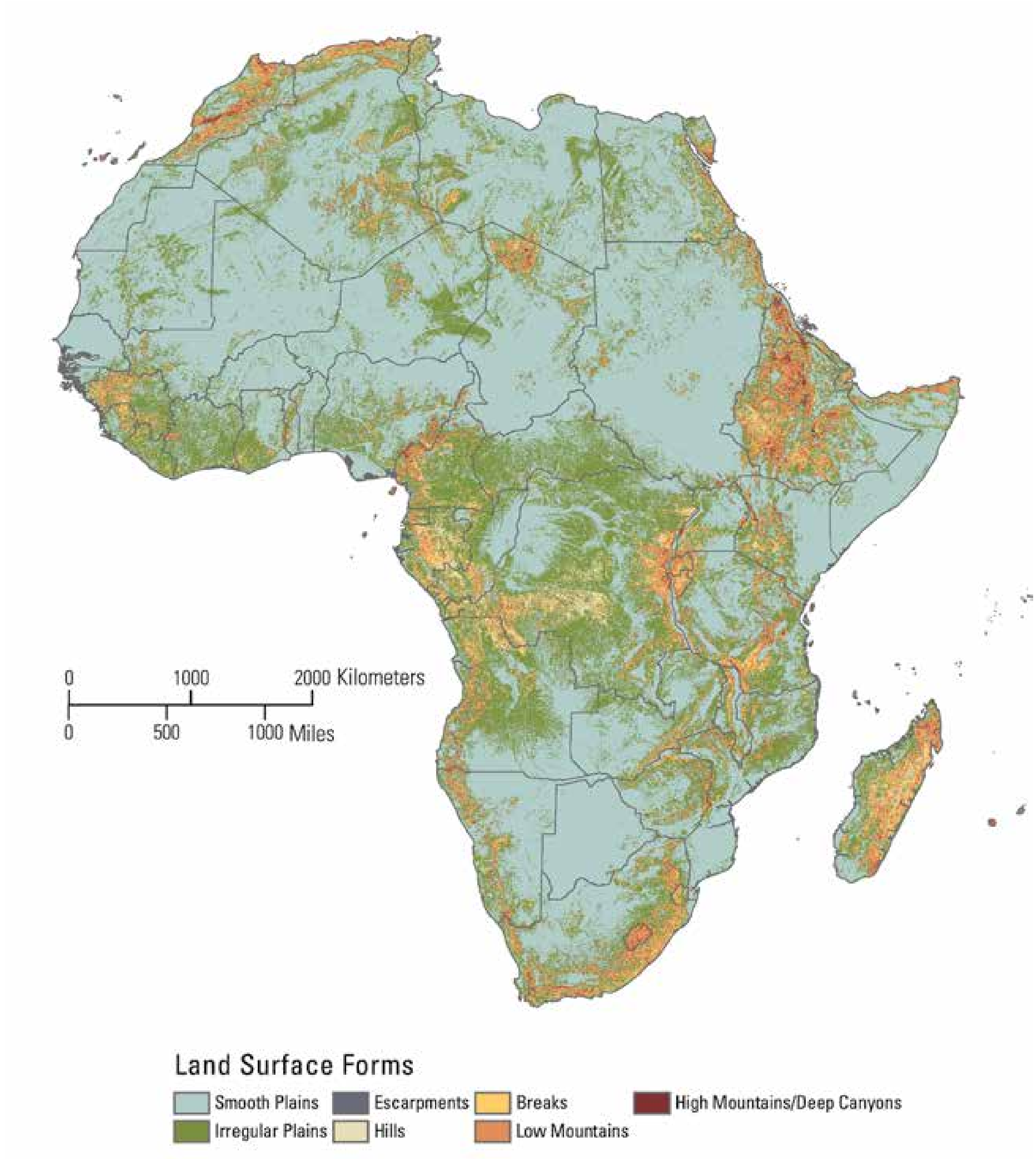


Figure 2 – Surficial lithology

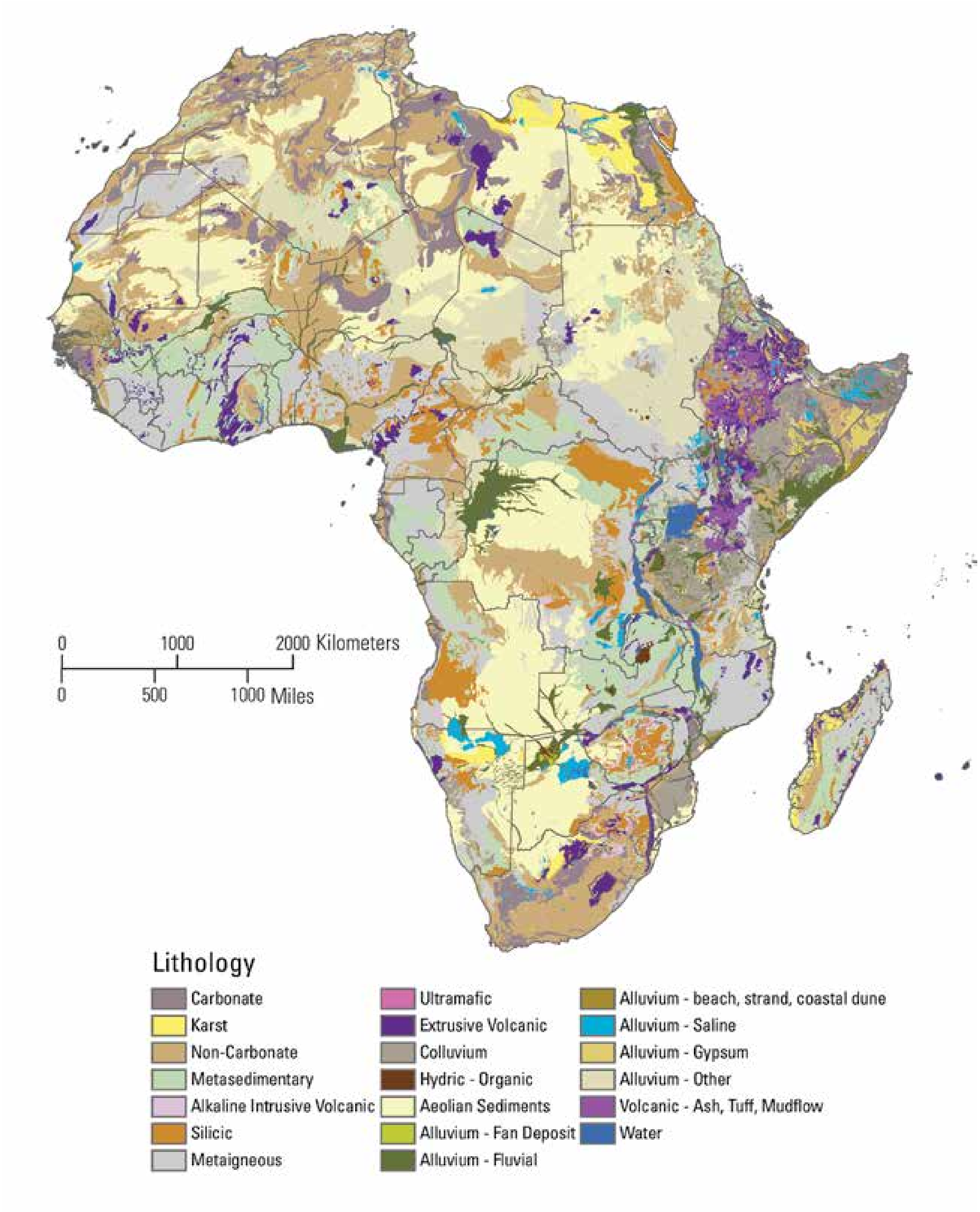


Figure 3 - Bioclimates

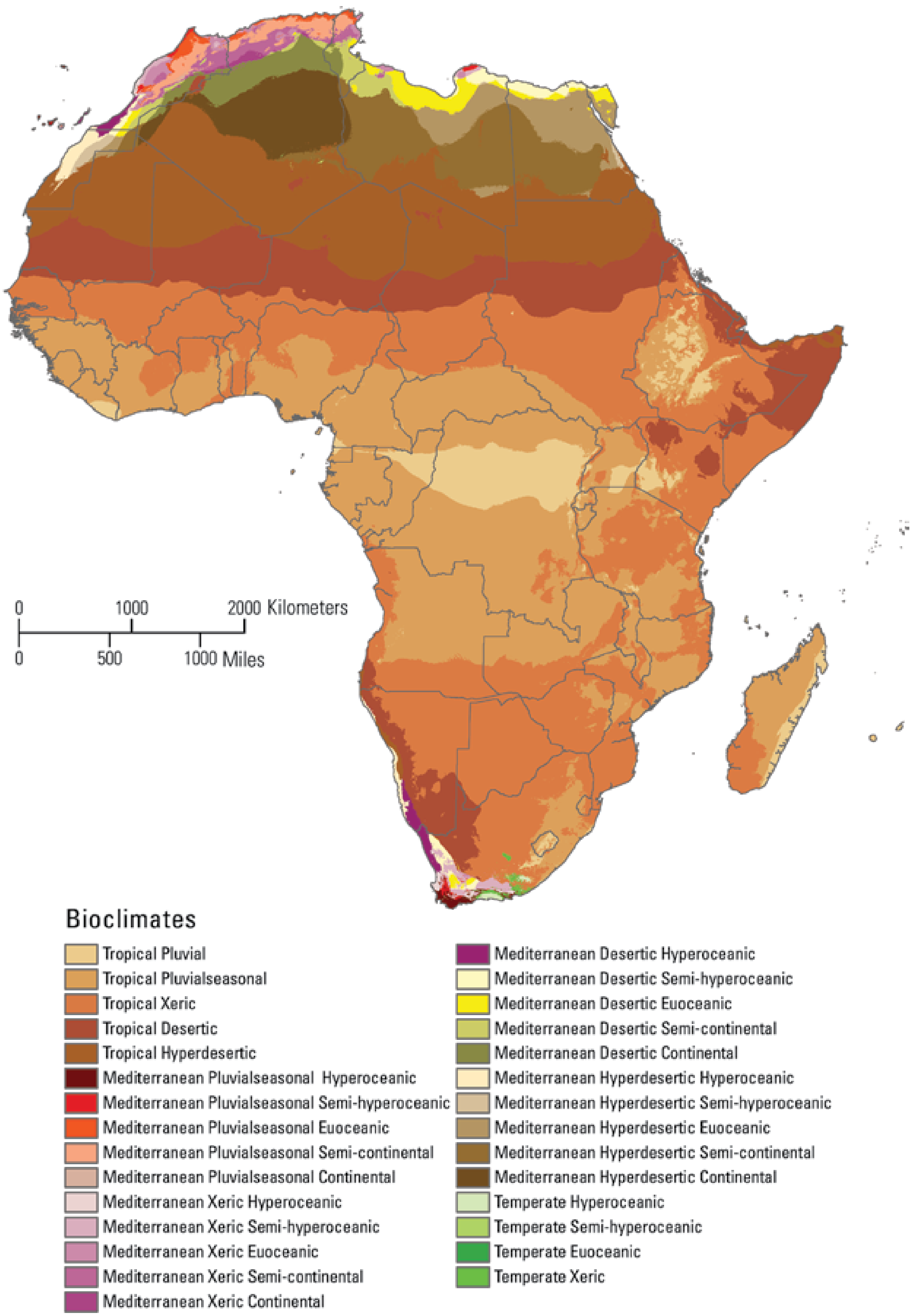


Figure 4 - Thermotypes

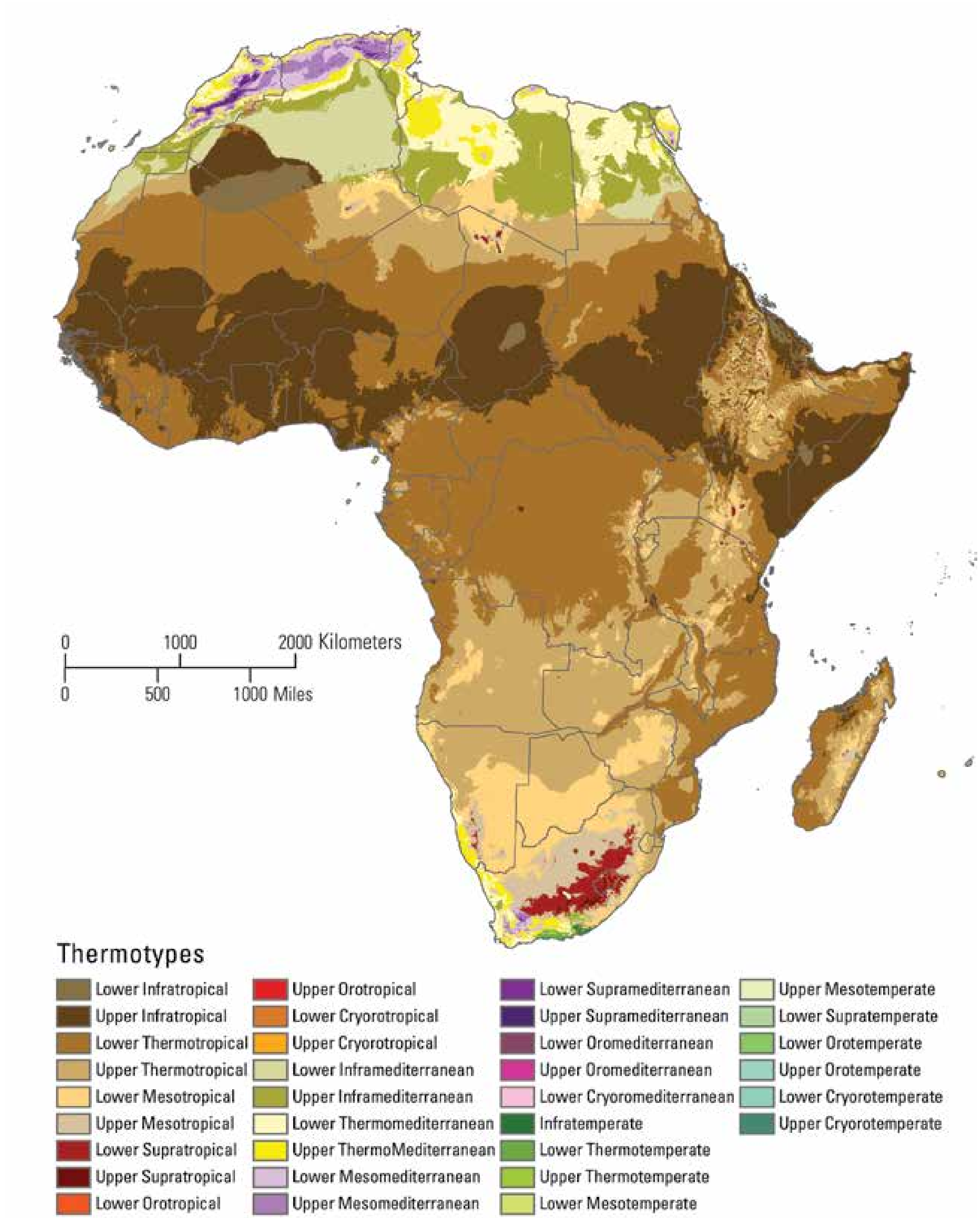


Figure 5 - Ombrotypes

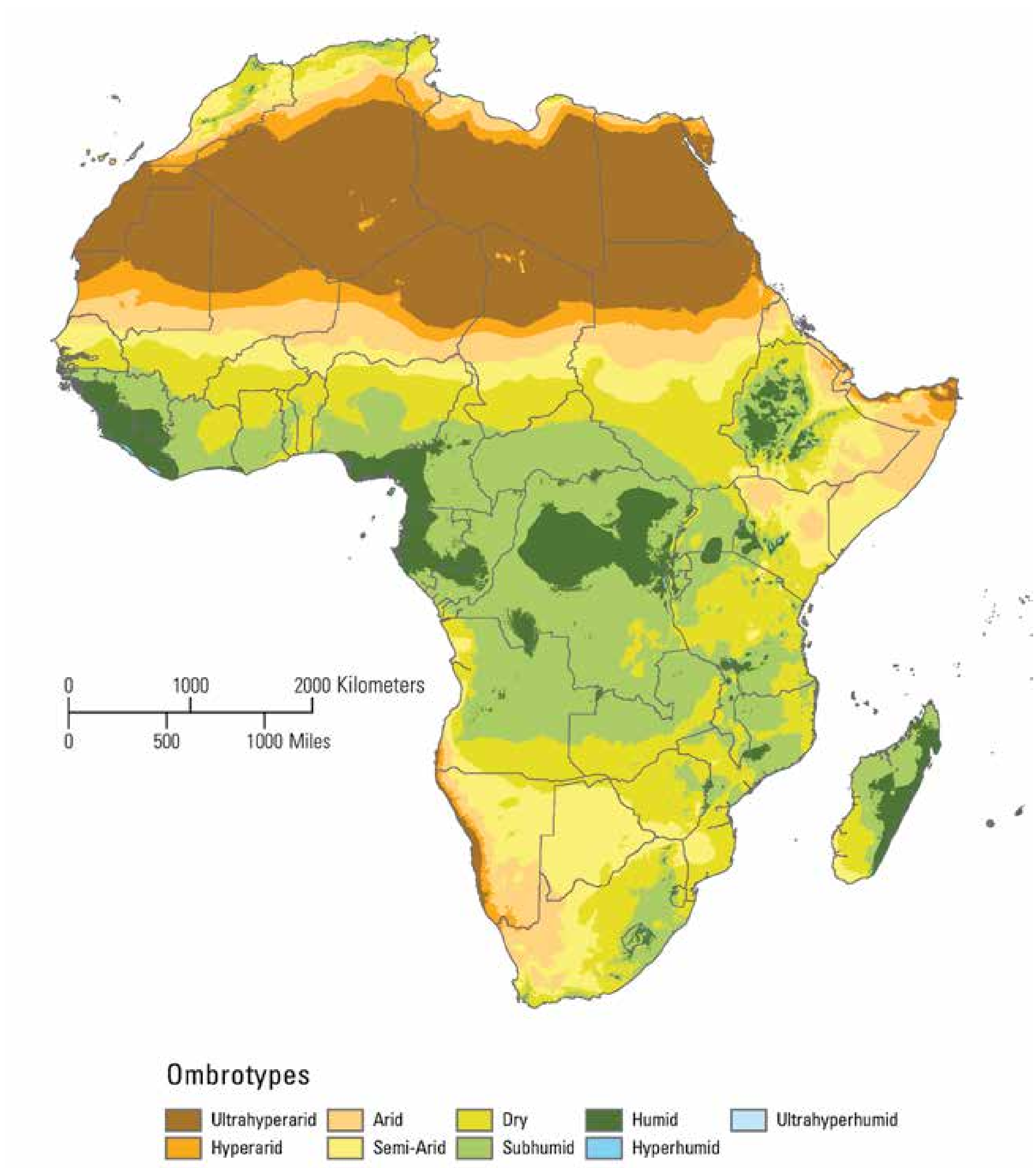
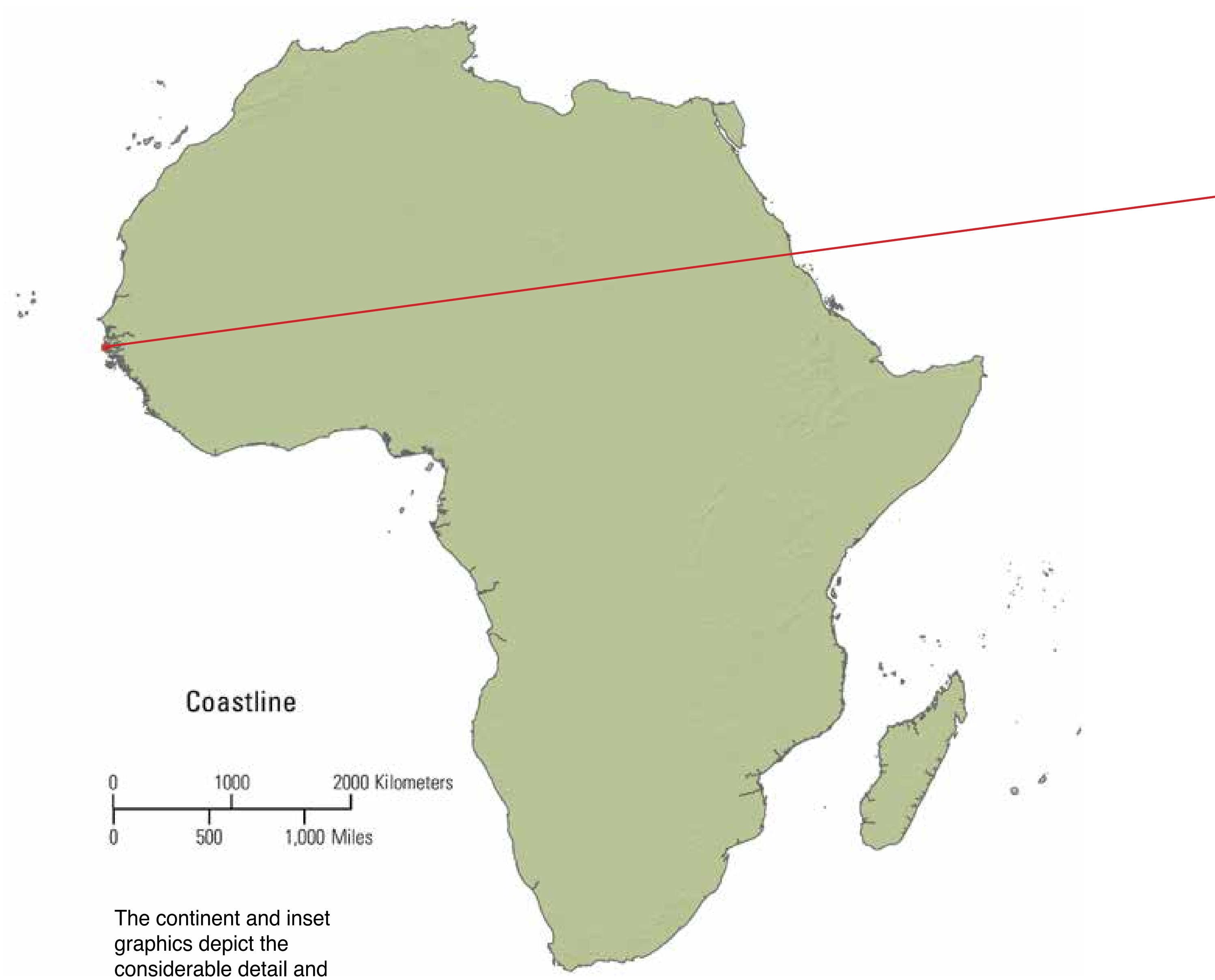
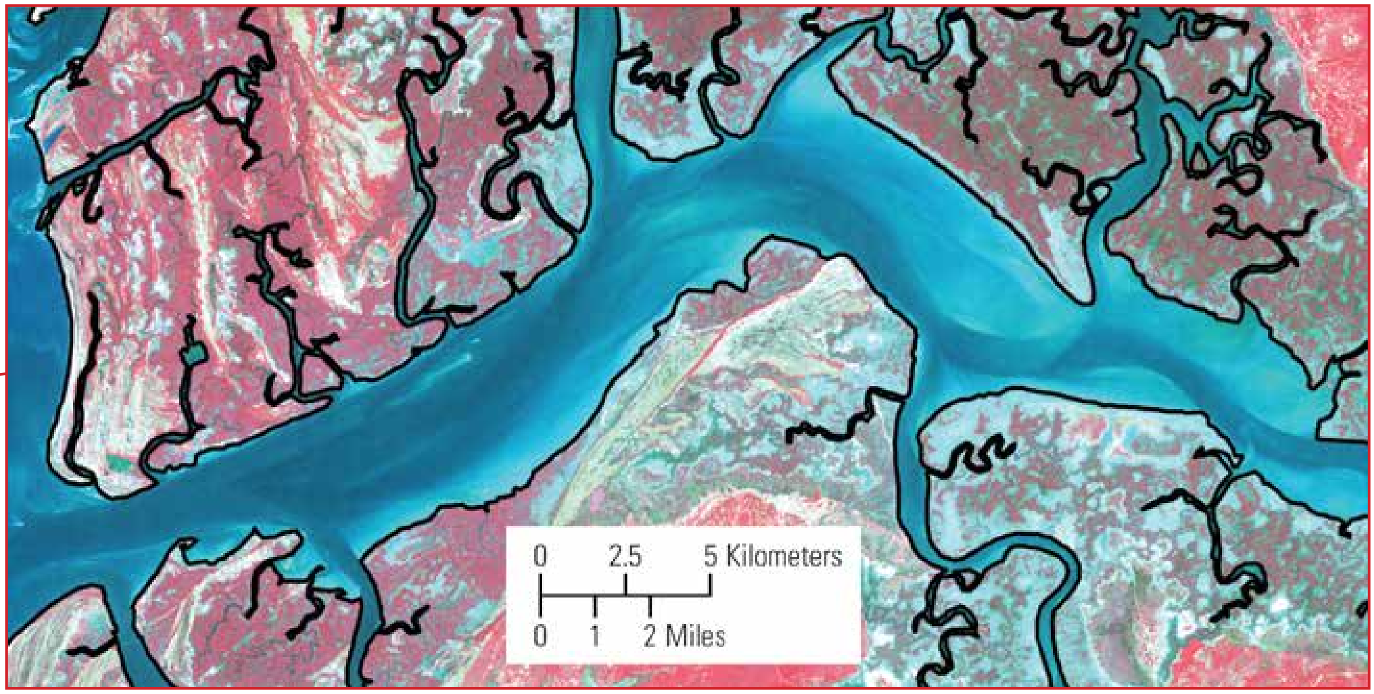


Figure 6 – Coastline and inset map showing detail of coastline vector development



The continent and inset graphics depict the considerable detail and fine spatial resolution (30 m) of the coastline vector developed for this study.



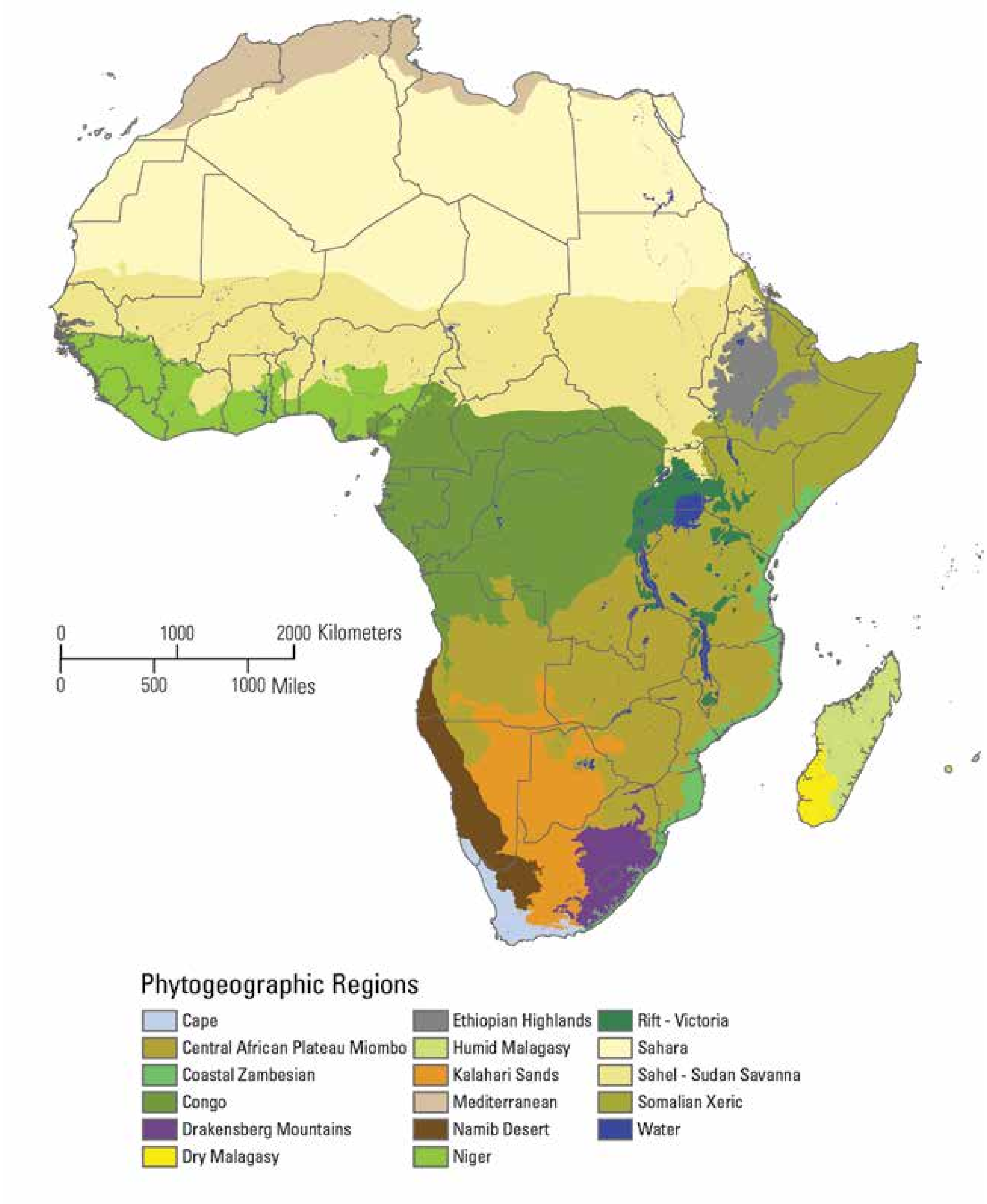
Phytogeographic Regions

In addition to characterizing the physical environment, we also developed a generalized phytogeographic regions layer (Figure 7) as another input to the classification and regression tree approach. Including a general biogeography layer in the model facilitates the separation of similar vegetative growth forms that occur in different geographic areas. For example, tropical rain forests occur in both the Congo and in Madagascar, but vary compositionally and structurally. The phytogeographic regions layer in the CART model allows a more efficient geographic allocation of vegetation types.

The general phytogeographic regions layer was developed as an aggregation and reconciliation of World Wildlife Fund's ecoregions (Burgess et al., 2004), White's (1983) and Takhtajan's (1986) phytogeography maps, and Bailey's (1998, 2009) sub-continental climate and physiographic regions. Twenty generalized phytogeogeographic regions were delineated using the WWF ecoregions as the "building blocks" in the aggregation process, and subsequently manually adjusting those boundaries using climatic/physiographic data.

It is important to note here that our approach to delineating terrestrial ecosystems emphasizes the distribution of unique vegetation assemblages in their biophysical settings. Our characterization of the biophysical context includes the climate regime (ombrotypes and thermotypes) and the geomorphology (lithology and landforms). We recognize that other environmental factors (e.g. surface moisture potential, Sayre et al., 2009) have been used to characterize the biophysical context in which vegetation exists, and could be incorporated into future modeling efforts. It is also important to note that while phytogeography is an important component of our ecosystem mapping approach, zoogeography was not incorporated. As a result, the ecosystem units mapped herein, while very appropriate for understanding vegetation distributions, may not be as appropriate for understanding the distribution of fauna. The utility of these vegetation emphasizing ecosystems for animal habitat studies remains to be determined.

Figure 7 – Phytogeographic regions



Ecosystem Modeling Results

The input layers described and depicted above for landforms, lithology, bioclimates, thermotypes, ombrotypes, and biogeographic regions were used as predictor variables in the CART analysis. In addition to their utility for predicting ecosystem distributions, these datalayers have considerable potential in and of themselves for a variety of other applications ranging from agricultural planning to biodiversity analysis. With the exception of the biogeographic regions layer, which is a generalization of existing ecoregional datalayers, each input layer represents the finest spatial and classification (thematic) resolution, continent-wide dataset yet available for that theme.

For the CART analysis, these layers, as well as several additional layers (DEM, slope, aspect, thermotype and ombrotype) were used as predictor datasets. Point samples representing 32,078 known locations of the newly described vegetation types were used in the analysis. The modeling approach for the continent was divided into a sub-Saharan (24,366 point samples) and Madagascar (5,388 point samples) regional subset, and a Northern African and Mediterranean (2,324 point samples) subset. For the Northern African and Mediterranean analysis, a 150 m spatial resolution Landsat 7-derived satellite image mosaic (http://www.earthsat.com/NaturalVue/) was used as a CART input, in addition to the biophysical settings datasets, to distinguish among sparsely vegetated ecosystems.

The point samples were either provided by experts based on their knowledge of vegetation distributions, or derived from high quality existing maps where the mapped vegetation types were first reconciled to the newly described classification units at each level of the classification hierarchy. CART analysis was implemented sequentially for each level in the hierarchy, starting with the coarsest level (class), and finishing at the finest level (macrogroup type). Results obtained from modeling at each hierarchical level were then used as a predictor layer for modeling the next, more detailed, level of classification. Selected point samples were held out of each modeling run for subsequent use in map validation. The number and type of input layers used in the CART analysis were adjusted following each model run to improve robustness.

The model output, potential ecosystems, is not readily amenable to classical model validation as it represents the potential of the landscape to support vegetation assemblages, for which reference standards for Kappa statistics-based comparison analyses are lacking. The limited number of sample points, and uncertainty in known locations of the sample points that were used, also precludes a rigorous assessment of classification and map accuracy. The internal model performance was assessed by professional review and examination of the training data. The two regional models (sub-Sahara plus Madagascar, and North Africa) each had adequate to good internal model validation, with 12.5% and 2.2% error, respectively, in training point self-validation. The addition of the Landsat mosaic as a CART input for the North Africa model was a substantial contributor to model performance improvement.

The results of the mapping for the finest hierarchical level of ecosystems (vegetation macrogroups) are shown in Figures 8 (map) and 9 (legend) on Pages 16-17. A total of 163 macrogroup types were identified and described as potential ecosystem mapping units (Appendix). Of these, 126 ecosystems were mapped. For the 37 ecosystems that were described but not mapped, either the number of samples for the modeling was inadequate, very similar systems were not distinguished in the modeling, or the ecosystem occurrences were too small to be mapped (small patch ecosystems such as springs or bluff faces, etc.) at the 90 m spatial resolution. The datasets used to produce the new ecosystems maps, and the new ecosystems datalayer itself, are freely available online.[5] The ecosystem datalayer is vertically coherent with the biophysical settings datalayers, such that for any 90 m pixel in Africa, the values for the most probable vegetation macrogroup (ecosystem) occurring in that pixel, as well as its landform type, lithology, and bioclimate region are known and accessible. Ideally, an extensive field campaign to assess the accuracy of the resultant mapped vegetation types as well as the physical environment characterizations would be conducted; however, such a continental accuracy assessment is outside the scope of this current effort.

We are confident that improvements in the approach could be realized from focused new investments in data inputs and methodological development. It is hoped that in addition to the improvement of the vegetation classification, the African landscape ecology and ecosystem geography community will assess both the accuracy and utility of these datasets at regional, national, and local scales, and suggest improvements to the overall approach.

Figure 8 – Terrestrial ecosystems

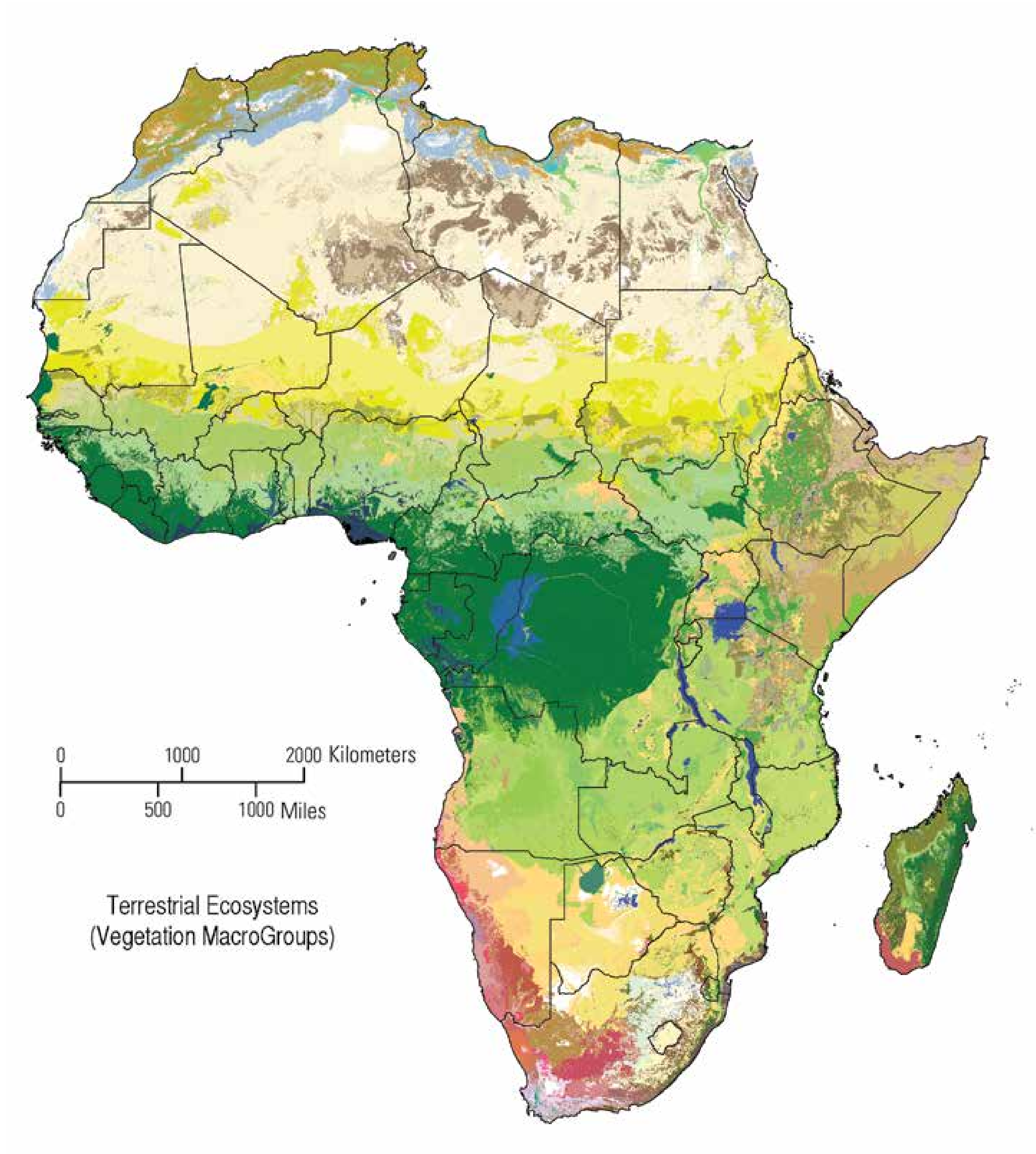


Figure 9 – Legend for terrestrial ecosystems map, preceding page

1.A Tropical Forest
- 1.A.1.Fe.1-Madagascar Western Dry Forest
- 1.A.1.Fe.2-Madagascar Tapia Forest
- 1.A.1.Ff.2-Eastern African Coastal Dry Semi-Deciduous Forest
- 1.A.1.Fg.1-Albany Subtropical Thicket
- 1.A.1.Fh.2-Maputaland Sand Forest
- 1.A.1.Fh.3-Zambesian Cryptosepalum Dry Forest
- 1.A.2.Fd.1-Guineo-Congolian Evergreen Rainforest
- 1.A.2.Fd.3-Guineo-Congolian Semi-Deciduous Rainforest
- 1.A.2.Fd.4-Guineo-Congolian Littoral Rainforest
- 1.A.2.Fe.1-Eastern Madagascar Lowland Rainforest
- 1.A.2.Fe.2-Eastern Madagascar Subhumid Forest
- 1.A.2.Fe.3-Western Madagascar Subhumid Forest
- 1.A.2.Fe.4-Western Madagascar Humid Forest
- 1.A.2.Fe.5-Madagascar Evergreen Littoral Forest
- 1.A.2.Ff.1-Eastern African Lowland Semi-Evergreen Forest
- 1.A.2.Ff.2-Central Indian Ocean Coastal Forest
- 1.A.2.Ff.3-Southern Indian Ocean Coastal Forest
- 1.A.2.Ff.4-Southern African Scarp Forest
- 1.A.3.Fd.1-Eastern African Dry Evergreen Montane Forest
- 1.A.3.Ff.1-Eastern Madagascar Montane Forest
- 1.A.3.Ff.4-Moist Evergreen Montane Forest
- 1.A.4.Fe.1-Uapaca guineensis Swamp Forest
- 1.A.4.Fe.2-Makaranga Swamp Forest
- 1.A.4.Ff.1-Zululand-Mozambique Coastal Swamp Forest
- 1.A.4.Fg.1-Antostema - Alstoneia Swamp Forest
- 1.A.4.Fg.2-Raffia Swamp
- 1.A.4.Fg.3-Central Congo Basin Swamp Forest
- 1.A.4.Fh.1-Western African Non-Riverine Swamp Forest
- 1.A.5.Ua.1-Atlantic Ocean Mangrove
- 1.A.5.Wb.1-Indian Ocean Mangrove

1.B Temperate Forest
- 1.B.1.Fe.1-Southern Afrotemperate Forest
- 1.B.1.Fe.2-Northern Afrotemperate Forest
- 1.B.1.Fe.3-Southern Mistbelt Forest
- 1.B.1.Fe.4-Northern Mistbelt Forest
- 1.B.1.Ph.1-Mediterranean Lowland Mixed Forest
- 1.B.1.Ph.2-Northern African Pinus / Quercus Forest & Woodland
- 1.B.1.Ph.3-Mediterranean montane coniferous forest
- 1.B.3.Fe.1-Fynbos Flooded Riparian Thicket
- 1.B.3.Ff.1-Southern African Riparian Phreatophyte Vegetation

2.A Tropical Grassland, Savanna & Shrubland
- 2.A.1.Ff.2-Western African Mesic Woodland & Grassland
- 2.A.1.Ff.3-Gabono-Congolian Mesic Woodland & Grassland
- 2.A.1.Fg.1-Dry Combretum - Mixed Woodland & Savanna
- 2.A.1.Fg.2-Dry Acacia Woodland & Savanna
- 2.A.1.Fg.3-Dry Acacia - Terminalia - Combretum Woodland & Savar
- 2.A.1.Fg.4-Southern Kalahari Dunefield Woodland & Savanna
- 2.A.1.Fg.5-Kalahari Camel Thorn Woodland & Savanna
- 2.A.1.Fh.1-Limpopo Mopane
- 2.A.1.Fh.2-Zambezi Mopane
- 2.A.1.Fh.3-Namibia-Angola Mopane
- 2.A.1.Fi.1-Sudano-Sahelian Herbaceous Savanna
- 2.A.1.Fi.2-Sudano-Sahelian Shrub Savanna
- 2.A.1.Fi.3-Sudano-Sahelian Treed Savanna
- 2.A.1.Fn.1-Wet Miombo
- 2.A.1.Fn.2-Dry Miombo
- 2.A.1.Fn.3-Baikiaea Woodland & Savanna
- 2.A.1.Fo.1-Moist Combretum - Terminalia Woodland & Savanna
- 2.A.1.Fo.2-Moist Acacia - (Combretum) Woodland & Savanna
- 2.A.1.Fp.1-Madagascar Plateau Woodland & Grassland
- 2.A.1.Fq.1-Malagasy Subhumid Woodland & Savanna
- 2.A.2.Fe.2-Afro-Alpine Moorland
- 2.A.2.Fe.3-Afromontane Grassland
- 2.A.2.Fj.1-Malagasy Montane Scrub
- 2.A.5.Fc.1-African Tropical Freshwater Marsh (Dembos)
- 2.A.5.Fc.4-African Temperate Moorland
- 2.A.5.Fd.1-Okavango-Cuvelai Phreatophyte Vegetation
- 2.A.5.Pm.1-Date Palm Oasis
- 2.A.5.Pm.2-Northern African Alluvial Wash & Riparian Vegetation
- 2.A.5.Pm.4-Sahelian Riparian Forest
- 2.A.5.Pm.5-Northern African Flooded Riparian Woodland
- 2.A.5.Pm.6-Northern African Riparian Phreatophyte Vegetation

2.B Temperate Grassland & Shrubland
- 2.B.1.Fh.1-Fynbos
- 2.B.1.Fh.2-Renosterveld
- 2.B.1.Fh.3-Strandveld
- 2.B.1.Pk.1-Mediterranean Montane Scrub
- 2.B.1.Pk.2-Mediterranean Lowland Scrub
- 2.B.2.Fm.1-Drakensberg Grassland
- 2.B.2.Fm.2-Dry Highveld Grassland
- 2.B.2.Fm.3-Moist Highveld Grassland
- 2.B.2.Fm.4-Sub-Escarpment Grassland
- 2.B.6.Fd.1-African Temperate Freshwater Marsh
- 2.B.6.Fd.2-African Temperate Vernal Pool
- 2.B.7.Fg.1-African Cape Coastal Salt Marsh
- 2.B.7.Fh.1-Tropical African Coastal Salt Marsh
- 2.B.7.Fi.1-Eastern African Salt Marsh
- 2.B.7.Fj.1-Etosha Salt Pan
- 2.B.7.Fj.2-Kalahari Salt Pan
- 2.B.7.Fj.3-Bushmanland-Highveld Salt Pan
- 2.B.7.Fj.4-Lowveld-Limpopo Salt Pan
- 2.B.7.Pr.1-Saharan Mediterranean Salt Pan
- 2.B.7.Pr.2-Somalia-Masai Salt Pan
- 2.B.7.Ps.1-Mediterranean Coastal Salt Marsh

3.A Warm Desert & Semi-Desert Woodland, Scrub & Grassland
- 3.A.2.Fc.1-Richtersveld
- 3.A.2.Fc.2-Namaqualand Hardeveld
- 3.A.2.Fc.3-Namaqualand Sandveld
- 3.A.2.Fc.4-Knersvlakte
- 3.A.2.Fc.5-Trans-Escarpment Succulent Karoo
- 3.A.2.Fc.7-Sperregebied Succulent Karoo
- 3.A.2.Fd.1-Madagascar Southwestern Coastal Bushland
- 3.A.2.Fd.2-Madagascar Southwestern Dry Forest-Thicket
- 3.A.2.Fe.1-Eastern African Bushland & Thicket
- 3.A.2.Fe.2-Eastern African Semi-Desert Scrub
- 3.A.2.Fe.3-Eastern African Acacia Woodland
- 3.A.2.Fe.4-Eastern African Acacia - Commiphora Woodland
- 3.A.2.Fh.1-Bushmanland Semi-Desert Scrub & Grassland
- 3.A.2.Fh.2-Upper Karoo Semi-Desert Scrub & Grassland
- 3.A.2.Fh.3-Lower Karoo Semi-Desert Scrub & Grassland
- 3.A.2.Fh.4-Southern Namibian Semi-Desert Scrub & Grassland
- 3.A.2.Fh.5-Pro-Namib Semi-Desert Scrub
- 3.A.2.Fh.6-Kaokoveld Semi-Desert Scrub
- 3.A.2.Fi.1-Gariep Desert
- 3.A.2.Fi.2-Southern Namib Desert
- 3.A.2.Fi.4-Northern Namib Desert
- 3.A.2.Pf.1-North Sahel Herbaceous Steppe
- 3.A.2.Pf.2-North Sahel Shrubland Steppe & Grassland
- 3.A.2.Pf.3-North Sahel Treed Steppe & Grassland
- 3.A.2.Pg.1-Mountainous Saxicolous Grassland
- 3.A.2.Pg.2-Saharan Herbaceous Steppe
- 3.A.2.Pg.3-Saharan Shrub Steppe
- 3.A.2.Pg.4-Saharan Sandy Grassland
- 3.A.2.Pj.1-Saharan Desert Pavement
- 3.A.2.Pj.2-Saharan Desert Rock Outcrop
- 3.A.2.Pj.3-Saharan Desert Dune & Sand Plain

6.A Tropical Rock Vegetation
- 6.A.1.Fc.2-Atlantic African Coastal Dune
- 6.A.1.Fc.7-African Tropical Dune Vegetation

6.B Mediterranean, Temperate Rock Vegetation
- 6.B.2.Fd.2-African Temperate Dune Vegetation
- 6.B.2.Pe.1-Northern African Mediterranean Alpine Rock & Scree

- Water

Conclusion

This classification and map of the ecosystems of the entire African continent represents the most current and finest spatial and thematic resolution characterization of African vegetation in its biophysical context available today. Each of these ecosystem types is distributed on the landscape in multiple occurrences, and this patch-level mapping of repeating ecosystem units distinguishes the effort from coarser resolution ecoregion maps with essentially single, large polygon occurrences. The environmental datalayers created to model ecosystem distributions were derived from data, and used standardized algorithms from a larger global ecosystem mapping initiative under the GEOSS intergovernmental protocol.

The new ecosystem map for the continent has considerable potential utility for conservation priority setting. A gap analysis of the types and amounts of ecosystems currently represented in the protected area network of Africa is straightforward. Moreover, if the conservation of some percentage of the distribution of all unique terrestrial ecosystems in Africa is a conservation goal, this new ecosystems map could be used to design a portfolio of conservation areas that achieves the ecosystems representation goal. The map may also be suitable for use in climate change impacts studies which focus on the relationship between climate variability and ecosystem condition and distribution. Other types of impacts studies (fire, invasive species, agricultural expansion, etc.) could incorporate the new ecosystems data as well. The map may also have considerable utility for assessing carbon stocks and vegetative carbon sequestration potential.

Moreover, as the primary provisioning units of ecosystem goods and services (food, fiber, fuel, carbon sequestration, water provisioning and quality, etc.), these mapped ecosystems also have potential for spatially explicit studies of the economic and social value of ecosystem services in Africa.

We anticipate continued refinement of the classification and map as feedback is received on the accuracy and utility of these products, and we are grateful for that feedback.

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Notes

1. http://www.earthobservations.org/documents/work%20plan/GEO%202012-2015%20Work%20Plan_Rev2.pdf
2. http://www.earthobservations.org/documents/10-Year%20Plan%20Reference%20Document.pdf
3. http://rmgsc.cr.usgs.gov/outgoing/ecosystems/AfricaData/
4. FAO Africover Geomorphology/Landcover and Lithology Country Datasets – 2003, 1:350,000, for Burundi, Eritrea, Kenya, Rwanda, Somalia, and Tanzania

   South African Soil and Terrain (SOTERSAF) – 2003, 1:250,000 to 1:2,500,000 for Angola, Botswana, Mozambique, Namibia, South Africa, Swaziland, and Zimbabwe;

   Central African Soil and Terrain (SOTERCAF) – 2006, 1:1,000,000 to 1:2,000,000 for the Democratic Republic of the Congo;

   Northeastern African Soil and Terrain (SOTERNAF) – 1998, 1:1,000,000 for Djibouti, Egypt, Ethiopia, Sudan, and Uganda;

   Senegal Soil and Terrain (SOTWIS) – 2008, 1:1,000,000 for Senegal and Gambia;

   Madagascar Simplified Geology, Royal Botanic Gardens, KEW – 1998, 1:1,000,000, and

   Geologic Data Systems (GDS) Digital Geologic Map of the World: African Subset – 2008, 1:5,000,000.
5. http://rmgsc.cr.usgs.gov/outgoing/ecosystems/AfricaData/

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Appendix – Draft Vegetation and Ecosystem Classification for Africa

1 Forest to Open Woodland

1.A Tropical Forest

1.A.1 Tropical Seasonally Dry Forest

- 1.A.1.Fe Malagasy Dry Deciduous & Evergreen Forest & Woodland
  - 1.A.1.Fe.1-Madagascar Western Dry Forest
  - 1.A.1.Fe.2-Madagascar Tapia Forest
- 1.A.1.Ff Eastern African Dry Semi-Deciduous Forest
  - 1.A.1.Ff.1-Eastern African Dry Semi-Deciduous Forest
  - 1.A.1.Ff.2-Eastern African Coastal Dry Semi-Deciduous Forest
- 1.A.1.Fg Albany Subtropical Thicket
  - 1.A.1.Fg.1-Albany Subtropical Thicket
- 1.A.1.Fh Southern African Dry Tropical Forest
  - 1.A.1.Fh.1-Richtocephalum Dry Forest*
  - 1.A.1.Fh.2-Maputaland Sand Forest
  - 1.A.1.Fh.3-Zambesian Cryptosepalum Dry Forest

1.A.2 Tropical Lowland Humid Forest

- 1.A.2.Fd Guineo-Congolian Evergreen & Semi-Evergreen Rainforest
  - 1.A.2.Fd.1-Guineo-Congolian Evergreen Rainforest
  - 1.A.2.Fd.2-Guineo-Congolian Semi-Evergreen Rainforest*
  - 1.A.2.Fd.3-Guineo-Congolian Semi-Deciduous Rainforest
  - 1.A.2.Fd.4-Guineo-Congolian Littoral Rainforest
- 1.A.2.Fe Malagasy Evergreen & Semi-Evergreen Forest
  - 1.A.2.Fe.1-Eastern Madagascar Lowland Rainforest
  - 1.A.2.Fe.2-Eastern Madagascar Subhumid Forest
  - 1.A.2.Fe.3-Western Madagascar Subhumid Forest
  - 1.A.2.Fe.4-Western Madagascar Humid Forest
  - 1.A.2.Fe.5-Madagascar Evergreen Littoral Forest
- 1.A.2.Ff Eastern & Southern African Lowland Evergreen & Semi-Evergreen Forest
  - 1.A.2.Ff.1-Eastern African Lowland Semi-Evergreen Forest
  - 1.A.2.Ff.2-Central Indian Ocean Coastal Forest
  - 1.A.2.Ff.3-Southern Indian Ocean Coastal Forest
  - 1.A.2.Ff.4-Southern African Scarp Forest
  - 1.A.2.Ff.5-Zimbabwean-Malawian Subtropical Forest*
  - 1.A.2.Ff.6-Eastern Arc Subtropical Forest*
  - 1.A.2.Ff.7-Somalia-Masai Coastal Maritime Forest*

1.A.3 Tropical Montane Humid Forest

- 1.A.3.Fd Afromontane Dry Forest
  - 1.A.3.Fd.1-Eastern African Dry Evergreen Montane Forest
- 1.A.3.Ff Afromontane Moist Forest
  - 1.A.3.Ff.1-Eastern Madagascar Montane Forest
  - 1.A.3.Ff.2-Afromontane Mesic Forest*
  - 1.A.3.Ff.3-Entandrophragma - Newtonia - Parinari Forest*
  - 1.A.3.Ff.4-Moist Evergreen Montane Forest

1.A.4 Tropical Flooded & Swamp Forest

- 1.A.4.Fe Eastern African Swamp Forest
  - 1.A.4.Fe.1-Uapaca guineensis Swamp Forest
  - 1.A.4.Fe.2-Makaranga Swamp Forest
- 1.A.4.Ff Southern African Swamp Forest
  - 1.A.4.Ff.1-Zululand-Mozambique Coastal Swamp Forest
- 1.A.4.Fg Guineo-Congolian Swamp Forest
  - 1.A.4.Fg.1-Antostema - Alstoneia Swamp Forest
  - 1.A.4.Fg.2-Raffia Swamp
  - 1.A.4.Fg.3-Central Congo Basin Swamp Forest
- 1.A.4.Fh Sahelian Swamp Forest
  - 1.A.4.Fh.1-Western African Non-Riverine Swamp Forest
  - 1.A.4.Fh.2-Uapaca heudelotii Forest*
  - 1.A.4.Fh.3-West African Mitragyna Riverine Forest*
  - 1.A.4.Fh.4-Acacia Seasonally Flooded*

1.A.5 Mangrove

- 1.A.5.Ua Atlantic & Caribbean & East Pacific Mangrove
  - 1.A.5.Ua.1-Atlantic Ocean Mangrove
- 1.A.5.Wb Indo-West Pacific Mangrove
  - 1.A.5.Wb.1-Indian Ocean Mangrove

1.B Temperate & Boreal Forest

1.B.1 Warm Temperate Forest

- 1.B.1.Fe Southern African Warm Temperate Evergreen Forest
  - 1.B.1.Fe.1-Southern Afrotemperate Forest
  - 1.B.1.Fe.2-Northern Afrotemperate Forest
  - 1.B.1.Fe.3-Southern Mistbelt Forest
  - 1.B.1.Fe.4-Northern Mistbelt Forest
- 1.B.1.Ph Northern African Mediterranean Forest
  - 1.B.1.Ph.1-Mediterranean Lowland Mixed Forest
  - 1.B.1.Ph.2-Northern African Pinus / Quercus Forest & Woodland

1.B.3 Temperate Flooded & Swamp Forest

- 1.B.3.Fe Fynbos Riparian Thicket
  - 1.B.3.Fe.1-Fynbos Flooded Riparian Thicket
- 1.B.3.Ff Southern African Riparian Phreatophyte Vegetation
  - 1.B.3.Ff.1-Southern African Riparian Phreatophyte Vegetation

2 Shrubland & Grassland

2.A Tropical Grassland, Savanna & Shrubland

2.A.1 Tropical Lowland Grassland, Savanna & Shrubland

- 2.A.1.Ff West-Central African Mesic Woodland & Savanna
  - 2.A.1.Ff.1-Central African Mesic Woodland & Grassland*
  - 2.A.1.Ff.2-Western African Mesic Woodland & Grassland
  - 2.A.1.Ff.3-Gabono-Congolian Mesic Woodland & Grassland
- 2.A.1.Fg Eastern & Southern African Dry Savanna & Woodland
  - 2.A.1.Fg.1-Dry Combretum - Mixed Woodland & Savanna
  - 2.A.1.Fg.2-Dry Acacia Woodland & Savanna
  - 2.A.1.Fg.3-Dry Acacia - Terminalia - Combretum Woodland & Savanna
  - 2.A.1.Fg.4-Southern Kalahari Dunefield Woodland & Savanna
  - 2.A.1.Fg.5-Kalahari Camel Thorn Woodland & Savanna
- 2.A.1.Fh Mopane Savanna
  - 2.A.1.Fh.1-Limpopo Mopane
  - 2.A.1.Fh.2-Zambezi Mopane

2.A.1.Fh.3-Namibia-Angola Mopane
2.A.1.Fi Sudano-Sahelian Dry Savanna
2.A.1.Fi.1-Sudano-Sahelian Herbaceous Savanna
2.A.1.Fi.2-Sudano-Sahelian Shrub Savanna
2.A.1.Fi.3-Sudano-Sahelian Treed Savanna
2.A.1.Fn Miombo & Associated Broadleaf Savanna
2.A.1.Fn.1-Wet Miombo
2.A.1.Fn.2-Dry Miombo
2.A.1.Fn.3-Baikiaea Woodland & Savanna
2.A.1.Fn.4-Southern African Broadleaf Savanna*
2.A.1.Fn.5-Pericopsis Woodland & Savanna*
2.A.1.Fo Eastern African Moist Woodland & Savanna
2.A.1.Fo.1-Moist Combretum - Terminalia Woodland & Savanna
2.A.1.Fo.2-Moist Acacia - (Combretum) Woodland & Savanna
2.A.1.Fp Malagasy Dry Forest & Scrubland
2.A.1.Fp.1-Madagascar Plateau Woodland & Grassland
2.A.1.Fp.2-Madagascar Wooded Grassland-Bushland*
2.A.1.Fq Malagasy Subhumid Woodland & Savanna
2.A.1.Fq.1-Malagasy Subhumid Woodland & Savanna
2.A.2 Tropical Montane Grassland & Shrubland
2.A.2.Fe African Montane Grassland & Shrubland
2.A.2.Fe.1-African Subalpine Grassland & Moorland*
2.A.2.Fe.2-Afro-Alpine Moorland
2.A.2.Fe.3-Afromontane Grassland
2.A.2.Fj Malagasy Montane Thicket & Sclerophyllous Shrubland
2.A.2.Fj.1-Malagasy Montane Scrub
2.A.5 Tropical Freshwater Marsh, Wet Meadow & Shrubland
2.A.5.Fc Tropical Herbaceous Swamp & Aquatic Vegetation
2.A.5.Fc.1-African Tropical Freshwater Marsh (Dembos)
2.A.5.Fc.2-Malagasy Tropical Freshwater Marsh*
2.A.5.Fc.3-Sudano Tropical Riverine Marsh*
2.A.5.Fc.4-African Temperate Moorland
2.A.5.Fd Southern African Phreatophyte Vegetation
2.A.5.Fd.1-Okavango-Cuvelai Phreatophyte Vegetation
2.A.5.Fd.2-Eastern African Alluvial Wash*
2.A.5.Fd.3-Karoo Flooded Riparian Woodland*
2.A.5.Pm Northern African Phreatophyte Vegetation
2.A.5.Pm.1-Date Palm Oasis
2.A.5.Pm.2-Northern African Alluvial Wash & Riparian Vegetation
2.A.5.Pm.3-Western African Depressional Vegetation*
2.A.5.Pm.4-Sahelian Riparian Forest
2.A.5.Pm.5-Northern African Flooded Riparian Woodland
2.A.5.Pm.6-Northern African Riparian Phreatophyte Vegetation
2.A.5.Pm.7-Saharan Swamp Grassland*

2.B Temperate & Boreal Grassland & Shrubland

2.B.1 Mediterranean Scrub & Grassland
2.B.1.Fh South African Cape Mediterranean Scrub
2.B.1.Fh.1-Fynbos
2.B.1.Fh.2-Renosterveld
2.B.1.Fh.3-Strandveld
2.B.1.Fh.4-Cape Thicket*
2.B.1.Pk Northern African Mediterranean Scrub
2.B.1.Pk.1-Mediterranean Montane Scrub
2.B.1.Pk.2-Mediterranean Lowland Scrub
2.B.1.Pl Mediterranean Alpine Scrub & Herbaceous
2.B.1.Pl.1-Northern African Mediterranean Alpine Scrub & Herbaceous*
2.B.2 Temperate Grassland, Meadow & Shrubland
2.B.2.Fm Southern African Montane Grassland
2.B.2.Fm.1-Drakensberg Grassland
2.B.2.Fm.2-Dry Highveld Grassland
2.B.2.Fm.3-Moist Highveld Grassland
2.B.2.Fm.4-Sub-Escarpment Grassland
2.B.2.Fm.5-Southern Afromontane Grassland*
2.B.6 Temperate & Boreal Freshwater Marsh, Wet Meadow & Shrubland
2.B.6.Fd African Temperate Herbaceous Swamp & Aquatic Vegetation
2.B.6.Fd.1-African Temperate Freshwater Marsh
2.B.6.Fd.2-African Temperate Vernal Pool
2.B.7 Salt Marsh
2.B.7.Fg Southern African Temperate Coastal Marsh
2.B.7.Fg.1-African Cape Coastal Salt Marsh
2.B.7.Fg.2-Namib Sabkha Salt Marsh*
2.B.7.Fh Tropical Coastal Salt Marsh
2.B.7.Fh.1-Tropical African Coastal Salt Marsh
2.B.7.Fi Eastern African Salt Pan
2.B.7.Fi.1-Eastern African Salt Marsh
2.B.7.Fj Southern African Salt Pan
2.B.7.Fj.1-Etosha Salt Pan
2.B.7.Fj.2-Kalahari Salt Pan
2.B.7.Fj.3-Bushmanland-Highveld Salt Pan
2.B.7.Fj.4-Lowveld-Limpopo Salt Pan
2.B.7.Pr Northern African Salt Pan
2.B.7.Pr.1-Saharan Mediterranean Salt Pan
2.B.7.Pr.2-Somalia-Masai Salt Pan
2.B.7.Ps Northern African Temperate Coastal Marsh
2.B.7.Ps.1-Mediterranean Coastal Salt Marsh
2.B.7.Ps.2-Red Sea Sabkha Salt Marsh

3 Desert & Semi-Desert

3.A Warm Desert & Semi-Desert Woodland, Scrub & Grassland

3.A.2 Warm Desert & Semi-Desert Scrub & Grassland
3.A.2.Fc Succulent Karoo
3.A.2.Fc.1-Richtersveld
3.A.2.Fc.2-Namaqualand Hardeveld
3.A.2.Fc.3-Namaqualand Sandveld
3.A.2.Fc.4-Knersvlakte
3.A.2.Fc.5-Trans-Escarpment Succulent Karoo
3.A.2.Fc.6-Rainshadow Valley Karoo
3.A.2.Fc.7-Sperregebied Succulent Karoo
3.A.2.Fd Madagascar Xeric Scrub & Grassland

3.A.2.Fd.1-Madagascar Southwestern Coastal Bushland
3.A.2.Fd.2-Madagascar Southwestern Dry Forest-Thicket
3.A.2.Fe Eastern African Xeric Scrub
3.A.2.Fe.1-Eastern African Bushland & Thicket
3.A.2.Fe.2-Eastern African Semi-Desert Scrub
3.A.2.Fe.3-Eastern African Acacia Woodland
3.A.2.Fe.4-Eastern African Acacia - Commiphora Woodland
3.A.2.Fh Nama Karoo Semi-Desert Scrub & Grassland
3.A.2.Fh.1-Bushmanland Semi-Desert Scrub & Grassland
3.A.2.Fh.2-Upper Karoo Semi-Desert Scrub & Grassland
3.A.2.Fh.3-Lower Karoo Semi-Desert Scrub & Grassland
3.A.2.Fh.4-Southern Namibian Semi-Desert Scrub & Grassland
3.A.2.Fh.5-Pro-Namib Semi-Desert Scrub
3.A.2.Fh.6-Kaokoveld Semi-Desert Scrub
3.A.2.Fi Namib-Gariep Desert
3.A.2.Fi.1-Gariep Desert
3.A.2.Fi.2-Southern Namib Desert
3.A.2.Fi.3-Namib Sand Sea
3.A.2.Fi.4-Northern Namib Desert
3.A.2.Pf North Sahel Semi-Desert Scrub & Grassland
3.A.2.Pf.1-North Sahel Herbaceous Steppe
3.A.2.Pf.2-North Sahel Shrubland Steppe & Grassland
3.A.2.Pf.3-North Sahel Treed Steppe & Grassland
3.A.2.Pf.4-Northern African Steppe
3.A.2.Pg Sahara Warm Desert Scrub & Grassland
3.A.2.Pg.1-Mountainous Saxicolous Grassland
3.A.2.Pg.2-Saharan Herbaceous Steppe
3.A.2.Pg.3-Saharan Shrub Steppe
3.A.2.Pg.4-Saharan Sandy Grassland
3.A.2.Pj Saharan Desert
3.A.2.Pj.1-Saharan Desert Pavement
3.A.2.Pj.2-Saharan Desert Rock Outcrop
3.A.2.Pj.3-Saharan Desert Dune & Sand Plain
3.A.2.Pj.4-Saharan Desert Rockland

6 Rock Vegetation

6.A Tropical Rock Vegetation

6.A.1 Tropical Cliff, Scree & Other Rock Vegetation
6.A.1.Fc African Tropical Cliff, Scree, Rock & Dune Vegetation
6.A.1.Fc.1-Central African Inselberg Vegetation
6.A.1.Fc.2-Atlantic African Coastal Dune
6.A.1.Fc.3-Malagasy Granite Outcrop Vegetation
6.A.1.Fc.4-Zimbabwean Inselberg Vegetation
6.A.1.Fc.5-Namibian Inselberg Vegetation
6.A.1.Fc.6-Western African Inselberg Vegetation
6.A.1.Fc.7-African Tropical Dune Vegetation
6.A.1.Fc.8-Sudano Rock Outcrop Sparse Vegetation*

6.B Mediterranean, Temperate & Boreal Rock Vegetation

6.B.2 Temperate & Boreal Cliff, Scree & Other Rock Vegetation
6.B.2.Fd African Temperate Cliff, Scree, Rock & Dune Vegetation
6.B.2.Fd.1-Southern African Temperate Inselberg Vegetation
6.B.2.Fd.2-African Temperate Dune Vegetation
6.B.2.Pe Mediterranean Alpine Rock & Scree
6.B.2.Pe.1-Northern African Mediterranean Alpine Rock & Scree

**Described type, but samples were insufficient to support mapping*

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