Dry forests in Madagascar: neglected and under pressure

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SUMMARY

The dry forests in Madagascar represent a remarkable tropical forest ecosystem, occupying almost the entire west slope of the island up to the very northern tip, especially on substrates associated with sedimentary formations. These forests span several woody vegetation types of the island, including (i) the southwestern coastal bushland, (ii) the southwestern dry spiny forest-thicket, and (iii) the western dry forest. These landscapes show a high degree of biodiversity with several centers of endemism hosting a globally unique fauna, with disparities in richness and diversity according to the groups, probably related to paleo-refugia. These landscapes also provide important ecosystem services for various ethnic groups residing along the coast, also hosting the only autochthonous group in Madagascar, the Mikea forest people. In this paper we review the scientific literature to highlight the importance of dry forests socio-ecological landscapes in order to identify knowledge gaps where future research is required to better inform management and policy to better balance conservation and development interests. For this, we recommend the adoption of transdisciplinary approaches that engage with a broad number of stakeholders in order to allow policy adaptations to better cope with current and future changes (e.g., agriculture, energy demands and needs).

Keywords: biodiversity, endemism, agriculture, mining, governance

Forêts sèches de Madagascar: négligées et sous pression

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Les forêts sèches de Madagascar représentent un remarquable écosystème tropical forestier et sont distribuées sur la quasi-totalité du versant occidental jusqu'à l'extrême nord de l'île, et plus particulièrement sur les terrains associés à des formations sédimentaires. Ces forêts comprennent plusieurs types de végétation sylvicole dont: (i) la formation buissonnante côtière du sud-ouest, (ii) la forêt sèche épineuse du sud-ouest, et (iii) la forêt sèche de l'ouest. Ces paysages abritent une importante biodiversité avec plusieurs centres d'endémisme qui hébergent des faunes uniques à l'échelle globale, avec des particularités en matière de richesse et de diversité en fonction des groupes, probablement liées aux paléo-refuges. Ces paysages fournissent également d'importants services écosystémiques pour les divers groupes ethniques résidant sur la bande côtière occidentale, notamment aux Mikea, qui sont le seul groupe autochtone reconnu pour Madagascar. Dans cet article, nous passons en revue la littérature scientifique pour souligner l'importance des paysages socio-écologiques des forêts sèches, afin d'identifier les lacunes de connaissance à combler pour mieux informer une gestion et une politique capables d'harmoniser les besoins de la conservation et du développement. Dans ce cadre, nous préconisons la nécessité des approches transdisciplinaires portées par un grand nombre de parties prenantes pour permettre les adaptations des politiques face aux changements actuels et futurs, comme, par exemple, pour l'agriculture et les besoins et les demandes en énergie.

El bosque seco de Madagascar: abandonado y bajo presión

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Los bosques secos de Madagascar representan un ecosistema de bosque tropical notable, que ocupa casi la totalidad de la ladera oeste de la isla hasta la punta norte, especialmente en sustratos asociados con formaciones sedimentarias. Estos bosques abarcan varios tipos de vegetación leñosa en la isla, como son (i) el matorral costero del suroeste, (ii) el monte bajo de matorral espinoso seco del suroeste, y (iii) el bosque seco occidental. Estos paisajes muestran un alto grado de biodiversidad que cuenta con varios focos de endemismos que albergan una fauna única a nivel mundial, que muestra disparidades en la riqueza y la diversidad de acuerdo con los grupos, probablemente relacionadas con los paleorefugios. Estos paisajes proporcionan también importantes servicios ecosistémicos para los diversos grupos étnicos que residen a lo largo de la costa, y en particular para el único grupo autóctono de Madagascar: los pobladores del bosque de Mikea. En este artículo revisamos la literatura científica para resaltar la importancia de los paisajes socioecológicos de bosque seco con el fin de identificar las lagunas de conocimiento que requieren investigación futura para informar mejor a la gestión y las políticas conducentes a un mejor equilibro entre la conservación y los intereses de desarrollo. Por ello, recomendamos los enfoques transdisciplinarios, mediante la participación de un amplio elenco de partes interesadas necesarias que permita cambios en las políticas con las que enfrentarse mejor a los cambios actuales y futuros (p. ej. en la agricultura, la demanda de energía y las necesidades).

INTRODUCTION

The tropical forest biome represents a mosaic of vegetation formations. These formations include rain forests, seasonally-dry forests, and mid-elevation cloud forests (Dirzo *et al.* 2011). Seasonally dry tropical forests (SDTF) alone account for about 42% of the potential tropical global vegetation (Murphy and Lugo 1995), a substantial portion of which comprise biodiversity hotspots, i.e., contain a high level of endemism (Joppa *et al.* 2013) and are amongst the most threatened and least protected terrestrial tropical ecosystems (Janzen 1988, Miles *et al.* 2006). However, a lack of spatial information on the distribution of SDTF, coupled with ambiguity in its definition, make it difficult to develop management strategies for the conservation of these globally important forests (Leimgruber *et al.* 2011).

Much of the research on tropical forests has focused on rainforests, where a growing knowledge base and understanding support research-based forest management and conservation decision-making. By comparison, little attention has been paid to dry forest systems (Janzen 1988, Pennington *et al.* 2000) even though they are facing growing challenges due to climatic and economic changes, which are difficult to predict (Carpenter and Gunderson 2001, Walker *et al.* 2002). Moreover, increasing complexity of forest systems due to increased risk and uncertainty poses a growing challenge for decision-makers seeking to identify management alternatives or new directions that can maximize, or at least balance, the range of decision criteria (e.g., Ananda and Herath 2009, Mendoza and Martins 2006). In this paper we present the case of Madagascar's dry forests.

Madagascar is renowned for its highly endemic biota, rich forests, and a wealth of other natural resources (Goodman and Benstead 2005, Raharimahefa 2012, Randriamalala and Liu 2010). However, Madagascar is plagued by environmental degradation, coupled with low agricultural productivity and poverty, ranking it 151st of 187 countries according to the Human Development Index, with a fast-growing population (13th highest birth-rate), 85% of which lives in rural areas and has an income of less than US$2 per day (CIA Worldfactbook 2013). Since 2009, political instability has undermined economic development amid the global financial crisis, which has accentuated impacts on the poor, leading to increased food insecurity (Randrianja 2012a). Already vulnerable to climate variability and extreme weather events (e.g., drought, cyclones), the country faces ever-increasing environmental vulnerability and degradation from anticipated climate change (Hannah *et al.* 2008).

The relatively densely populated central highlands are characterized by terraced, rice-growing valleys lying between grassy, deforested hills (Kull 2012). The eastern side of the island is mountainous and drops rather abruptly from the Central Highlands at circa 1 500 m altitude to the Indian Ocean in less than 100 km. These eastern slopes host most of the last remaining humid rainforest.

The western slopes are less densely populated, with the lowest population densities in the districts and regions of the Mahajanga and Toliara ex-provinces, which cover most of west and have 17.3 and 20.2 inhabitants/km^2, respectively, compared to an estimated national density of 36.9 inhabitants/km^2 in 2013 (INSTAT 2014).

Dry forests play an important socio-economic role in western Madagascar, providing building materials, firewood, medicinal plants, grazing habitat for cattle, and land reserves for future agricultural expansion. For example, household income in the municipality of South Soalara (southwestern Madagascar) overwhelmingly depends on maintaining herds of small ruminants in xerophytic bush and on producing charcoal (Rabeniala *et al.* 2009). Dry forests also contribute directly to ensuring food security of forest-dependent communities: the consumption of *Tenrec ecaudatus* (Schreber 1778) meat in the dry forests of Menabe reaches 0.75 kg per person per month (Raveloson 2011). This dependency on dry forests does not come without impact on the resource base. Indeed, the highest deforestation rate for dry forests in Africa between 1980 and 2000 has been observed in Madagascar with a loss of 18% (Miles *et al*. 2006); and the highest rate of deforestation in Madagascar between 2000 and 2005 was observed in spiny and dry forests, respectively, at 1.11% and 0.42% per year, as compared to 0.35% for rainforests (MEFT *et al*. 2009, Brinkmann *et al*. 2014, Zinner *et al*. 2014). Given the scale of dry forest degradation, effective decision making for management will require the capitalization of scientific information. The present paper reviews in the three sections Biodiversity, Conservation and policy, and Drivers of change the existing knowledge on Malagasy dry forests flora and fauna, ongoing conservation measures, and provides an analysis of the drivers of change. The objectives of this paper are to highlight the breadth and complexity of Madagascar's dry forest system and to identify and discuss research gaps.

METHODS

The current paper focuses on data and results obtained through a structured search of both published and unpublished secondary sources. The search for both, English and French literature was conducted from April to October 2013 using the online catalogues of Google Scholar, Scopus, ISI Web of Knowledge; key search terms were "seasonal dry tropical forests", "biodiversity/conservation/management/policy and dry forests" and a combination of these with the term "Madagascar". Our own collection related to Madagascar biodiversity in the Noe4D database is rich of some 9,000 references (Wilmé *et al.* 2012), and it has been used to document the taxa of interest here, from the link established between the taxa and the references within the database. Grey literature was mainly screened from organization whose work is also in or on dry forests, such as the Center for International Forestry Research (CIFOR), the International Union for Conservation Nature (IUCN), or the World Bank. The complexity of the topic is also reflected in the broad array of literature; to keep it at a manageable level, we have restricted ourselves to publications of the past two decades mainly.

The Noe4D biodiversity database considers only documents for which the faunal taxa have been accurately identified by specialists, and for which the locality as well as the date of observation for published references, or collection for specimens are known. The total samples presented here included 32 593 dated and georeferenced localities to document 115 endemic forest taxa of birds, 134 endemic forest taxa of mammals, 246 endemic taxa of amphibians and 352 endemic taxa of reptiles. The TROPICOS database and the Madagascar catalog, developed and maintained by the Missouri Botanical Garden, has been used to extract botanical information (Phillipson *et al*. 2006). Given many uncertainties with plant localities, the double-checked sample prepared for an IUCN red list assessment by the Groupe des Spécialistes des Plantes de Madagascar (2010) was considered here. The final botanical sample is composed of 28 169 specimens to document 1 503 endemic forest species.

To consider the dry forests within the system of protected areas, forest cover by Moat and Smith (2007) was used. This work has been recently updated, but solely based on remote sensing without any ground truthing (Anonymous 2013). Given the young age of these new estimates and the absence of feedback from practitioners in Madagascar, estimates for the forest cover are based on Moat and Smith (2007), and estimates for the Protected Areas and New Protected Areas are derived from Rebioma (2013).

BIODIVERSITY

Flora

Madagascar's flora is of a globally high richness, with thousands of species of vascular plants recognized, from an estimate of 13–14 000 (Phillipson *et al.* 2006) to less than 12 000 species more recently and a major endemic component, at both the species and genus level (Buerki *et al.* 2013). Madagascar's relief and prevailing winds have shaped its flora into a windward (in the eastern portion of the island under the direct influence of the moist southeast Trade Winds) and a leeward flora (in the west, influenced by the drying effects as these winds descend after crossing over the central portion of the island) (Perrier de la Bâthie 1921). A continental north-south divide, with three summits exceeding 2000 m in height, separates the eastern and western watersheds (Wilmé *et al.* 2006). There is a north-south, and an east-west gradient in precipitation, with declining precipitation and length of the rainy season towards the south and west of the island (Cornet 1974). On the eastern slopes, the dry season can reach four months, with annual precipitation between 1 500 and 4 000 mm; in the west, the dry season can reach 5–7 months in the north, with 500–1 500 mm of rainfall, while in the extreme south, it can extend to 12 months, with less than 300 mm of annual precipitation. Edaphic conditions can further accentuate the effects of drought; for example, in the south, plants on sand and limestone-derived soils can exhibit xeromorphic adaptations that are characteristic of climax forms of vegetation (Moat and Smith 2007). The dry forests have been a lot drier, including in recent geological times, as during the early deglaciation in the Indian Ocean between 18 000 and 17 000 years ago when sea level was 134 m below current level (Lambeck *et al*. 2014), and certainly until stabilization of sea level at its present level which occurred only 3000–2500 years ago (Camoin *et al*. 2004, Waeber *et al*. in press). During the dry events of the paleoclimate oscillations, areas where wildlife had access to water, in places where large rivers flow or in residual reliefs, as in western Madagascar, were important refugia (Mercier and Wilmé 2013).

Western dry forest (referred to by White (1983) as West Malagasy dry deciduous forest) today covers an area of 31 800 km^2 and has been reduced since the 1970s by almost 40% (Moat and Smith 2007). This forest type occurs in western Madagascar, from the Mangoky river north to the Cap d'Ambre (the island's northern tip) (Figure 1). The altitudinal range for almost all of this forest type (99.4%) extends from sea level to about 900m a.s.l. Geologically, the forests are situated on Mesozoic limestone in the mid-western and north-western portions of the island; they occur on unconsolidated sand mainly along the west coast, and on sandstone, basement rocks, and lava outcrops near Montagne d'Ambre (Figure 1) (Moat and Smith 2007). This forest type is diverse and forms impenetrable thickets as well as bushland and low scrub; the majority is deciduous, with the exception of riparian forms along water courses. Typical *thicket* components contain the following elements: *Acacia* spp., *Albizia* spp., *Commiphora* spp., and *Grewia grevei* Baill. Dominant forest species include *Adansonia* spp., *Dalbergia* spp. and *Stereospermum* spp. *Bushland* elements include *Acacia bellula* Drake, *Commiphora simplicifolia* H. Perrier, *Didierea madagascariensis* Baill. and *Euphorbia tirucalli* L. (Moat and Smith 2007). *Dry dense deciduous forests* occur mainly in the mid-western sector (cf. Humbert and Cours Darne 1965). Species of *Commiphora*, *Dalbergia* and *Hildegardia* Schott & Endl. are dominant canopy trees, reaching up to 20m (Humbert and

Cours Darne 1965). *Xerophytic bushlike* vegetation (with xerophytic adaptations including tuber formation, fleshiness, and leaf-size reduction), found on limestone pavements and *tsingy* (the Malagasy word for heavily eroded karstic limestone formations), reaches heights of 3–6m; dominant elements are *Dalbergia* spp., *Delonix* spp., *Euphorbia* spp. and *Rhopalocarpus lucidus* Bojer. *Dry deciduous thickets* occur in the northeast, reaching to seven meters in height. Dominant species are: *Adansonia suarezensis* H. Perrier, *Albizia* spp., *Alchornea* spp., *Brachylaena* spp., *Dichrostachys* spp., *Euphorbia* spp. (including *E. stenoclada* Baill.) and *Grewia* spp. (Moat and Smith 2007). The distribution and extent of dry sclerophyllous forests are patchy throughout the entire western region, where they occur on rock pavements with thin soils. These forests are dominated by *Sarcolaena oblongifolia* F. Gérard, *Asteropeia labatii* G.E. Schatz, Lowry & A.-E. Wolf 1999, and *Leptolaena* spp.

Southwestern dry spiny forest-thicket (referred to by White (1983) as West Malagasy deciduous thicket) currently covers an area of 15 491 km^2; it has been reduced since the 1970s by around 30% (Moat and Smith 2007). This vegetation type is found along the west to the south coast of Madagascar (Figure 1) at altitudinal ranges from sea level to 300m a.s.l.; it occupies limestone plateaus (with shallow, or rocky/pavement limestone-derived soils) and ridges of basement rock and sandstone (with deeper sands or sandy-clay soils) (Figure 1) (Moat and Smith 2007). These forests are dominated by members of the family Didiereaceae (*Alluaudia* (Drake) Drake, *Alluaudiopsis* Humbert & Choux, *Didierea* Baill., and *Decarya* Choux) as well as species of *Euphorbia*.

Degraded southwestern dry spiny forest (referred to by White (1983) as West Malagasy deciduous thicket) covers an area of 9 255 km^2. Today, over 30% of these forests are under formal protection (Moat and Smith 2007). They are encountered from sea level up to 300m a.s.l., and the underlying substrate is composed of unconsolidated sands and Paleogene limestone plateaus (Figure 1). The physiognomy of this vegetation type depends on local rainfall and substrate conditions, and ranges from patchy forests to bushland and low scrub formations (Moat and Smith 2007). Dominant species are the same as in southwestern dry spiny forest-thicket; common elements associated with disturbance include non-native species of *Agave* L., *Bidens* L., *Opuntia*, *Prosopis* L. and *Solanum* L. (Moat and Smith 2007).

Southwestern coastal bushland (referred to by Humbert and Cours Darne (1965) as "wooded savannah", a term that should be referred to as "wooded grassland", cf. Lowry *et al.* (1997)) covers an area of 1 762 km^2; it has been reduced by almost one third since the 1970s (Moat and Smith 2007). This subtropical bushland is found along the south coast of Madagascar (Figure 1) up to 50m a.s.l. It grows on colluvial or aeolian unconsolidated sand and forms open stands (40% canopy cover) 3–7m in height (Moat and Smith 2007). Dominant tree species are: *Euphorbia stenoclada* and *E. tirucalli, Albizia atakataka* Capuron, *Azima tetracantha* Lam., *Boscia longifolia* Hadj-Moust., *Delonix floribunda* (Baill.) Capuron, *Salvadora angustifolia* Turrill, *Stereospermum nematocarpum* DC., and *Tamarindus indica* L. (which is native but not an endemic species (Diallo *et al.* 2007)). Its shrub layer is characterized by *Croton geayii* Leandri, *Solanum bumeliaefolium* Dunal, *Lasiosiphon decaryi* Leandri, *Marsdenia cordifolia* Choux, *Psiadia altissima* (DC.) Drake, *Physena sessiflora* Tul., *Mimosa* L., *Aloe vaombe* Decorse & Poisson and *A. divaricata* A. Berger and *Zygophyllum depauperatum* Drake (Moat and Smith 2007).

Fauna

Species richness

The taxa endemic to Madagascar within four classes of terrestrial vertebrates, namely Mammalia (mammals), Aves (birds), Reptilia (reptiles), and Amphibia (amphibians), and two groups of invertebrates, the order Scorpiones (scorpions) in the class of Arachnida, and the class Diplopoda (millipedes) are presented. Numbers within these groups are summarized in Table 1. The description of some of these species has started as early as in 1758, i.e., at the adoption of the binomial nomenclature, with the description of the ringtailed lemur (*Lemur catta* Linnaeus 1758), but the modern rise in taxa descriptions vary amongst these groups (Figure 2). It has long been admitted that most groups of invertebrates are still in need of major inventories and description by specialists (e.g., Paulian 2001). The species richness of the scorpions and millipedes show a rapid increase in the number of species with recent involvement of one or very few specialized taxonomist in each case (Table 1, Figure 2). The number of vertebrate species described for Madagascar has soared during the last decades, as exemplified for the reptiles which started with descriptions by Brygoo and Domergue, or more recently for the amphibians with descriptions by Glaw and Vences (Figure 2), bats by Goodman (2011) or lemurs (cf. Tattersall 2013).

On a global scale, species richness declines with distance to the equator and with increasing altitude, often with a mid-altitudinal hump in species richness (Hillebrand 2004, Kwon *et al*. 2014 and references therein). These gradients have been cited for the humid forests in Madagascar (e.g., Humbert 1965, Lourenço 1996, Soarimalala and Goodman 2011) but do not always or weakly apply for all groups, e.g., birds (Wilmé and Goodman 2003).

For the vertebrates and plants, the sample size is clearly biased towards humid and subhumid forests, including for the birds with twice as many records in the humid forests vs. dry forests (Table 2). Among the Malagasy mammals only 39% of the Afrosoricida, 41% of the Rodentia species, 62% of the Primates (species and subspecies) and 62% of the Carnivora species are found in the dry forests while 97%, 82%, 84% and 75% occur in the humid and subhumid forests, respectively (Figure 3).

Dry forests are known for their reptile richness. Although the number of sampled sites is relatively small compared to humid forests, the level of species richness comprises nearly 30% of the island's named herpetofauna as shown by an inventory of several dry forests sites by Raselimanana (2008a) which has recorded approximately 80% of the known dry forest herpetofauna. This study reported 188 endemic species

FIGURE 1 *Lithology and extension of sedimentary basins along the western slope of Madagascar following Besairie and Collignon (1971) (left); forest cover according to Moat and Smith (2007) (right)*

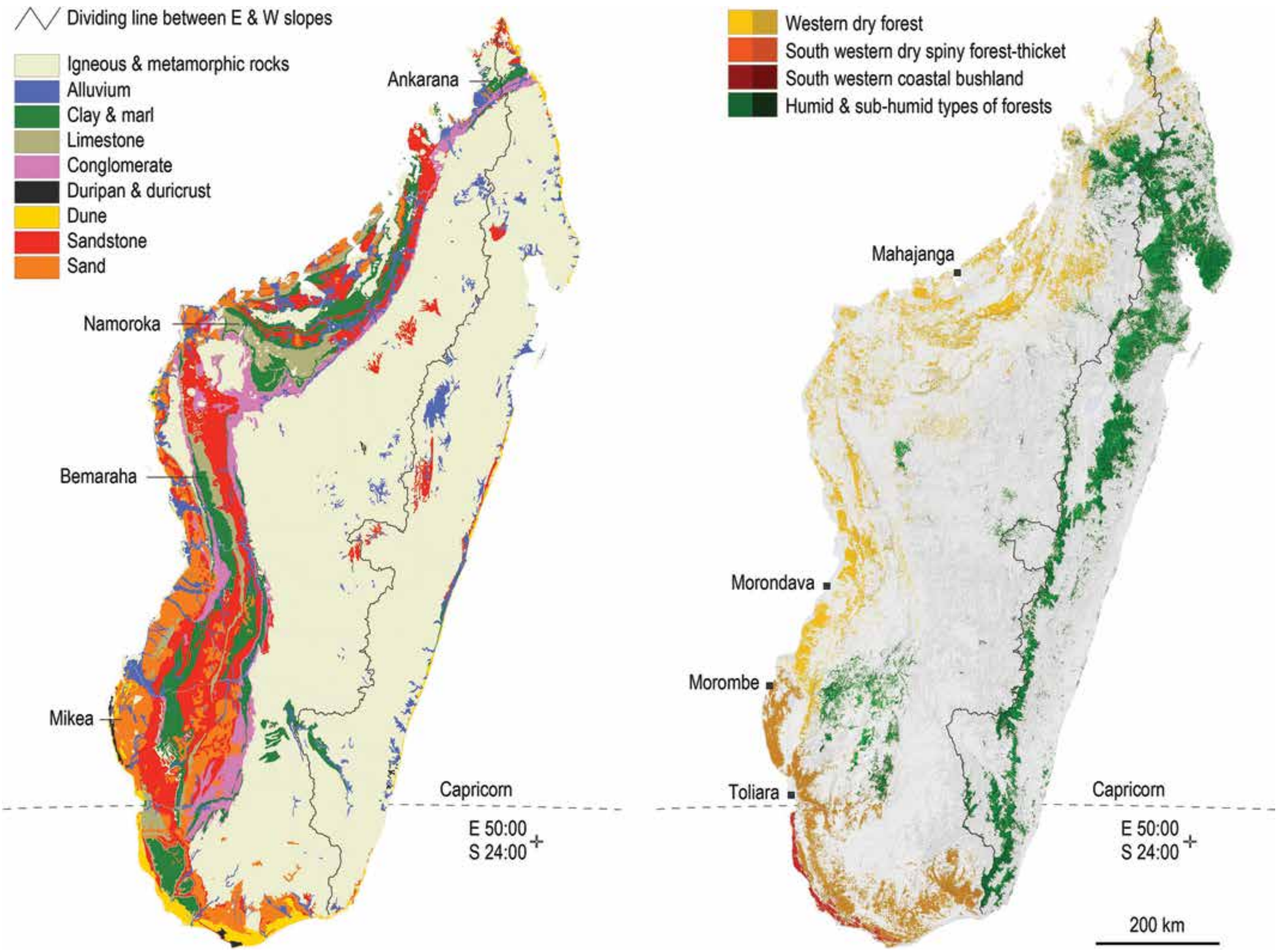


TABLE 1 *Endemic species and subspecies richness in six groups of animals (based on Noe4D compilation, Wilmé* et al. *2012)*

Taxonomical groups	Number of endemic species and subspecies currently recognized	Number of first authors in the description of the endemic species and subspecies	Endemic component/ autochthonous taxa
Scorpiones	76	6	100%
Diplopoda	119	9	99%
Amphibia	282	45	100%
Reptilia	396	75	97%
Aves	180	54	73%
Mammalia	212	70	95%

(34 amphibians and 154 reptiles) in the dry forests and surrounding areas. A total of 51% of the reptile species and 15% of Madagascar's amphibian species occur in the dry biome (Raselimanana 2008a). Climatic factors, substrate types, rivers, and different specific ecological parameters are correlated with the biogeographic patterns of the herpetofauna communities in the dry forests. Local reptile and amphibian communities show clear functional adaptations with regards to environmental conditions. The herpetofauna communities within Malagasy dry forests show remarkable levels of local endemism and specifically narrow-range endemism. Amongst the 30 species recorded in the dry forest, 14 species are only known from the dry forests. A remarkable narrow-range endemism characterize also the herpetofauna community of

FIGURE 2 *Description of currently recognized endemic species and subspecies in six groups of vertebrates and invertebrates. Pie charts show first authors describing taxa in respective groups*

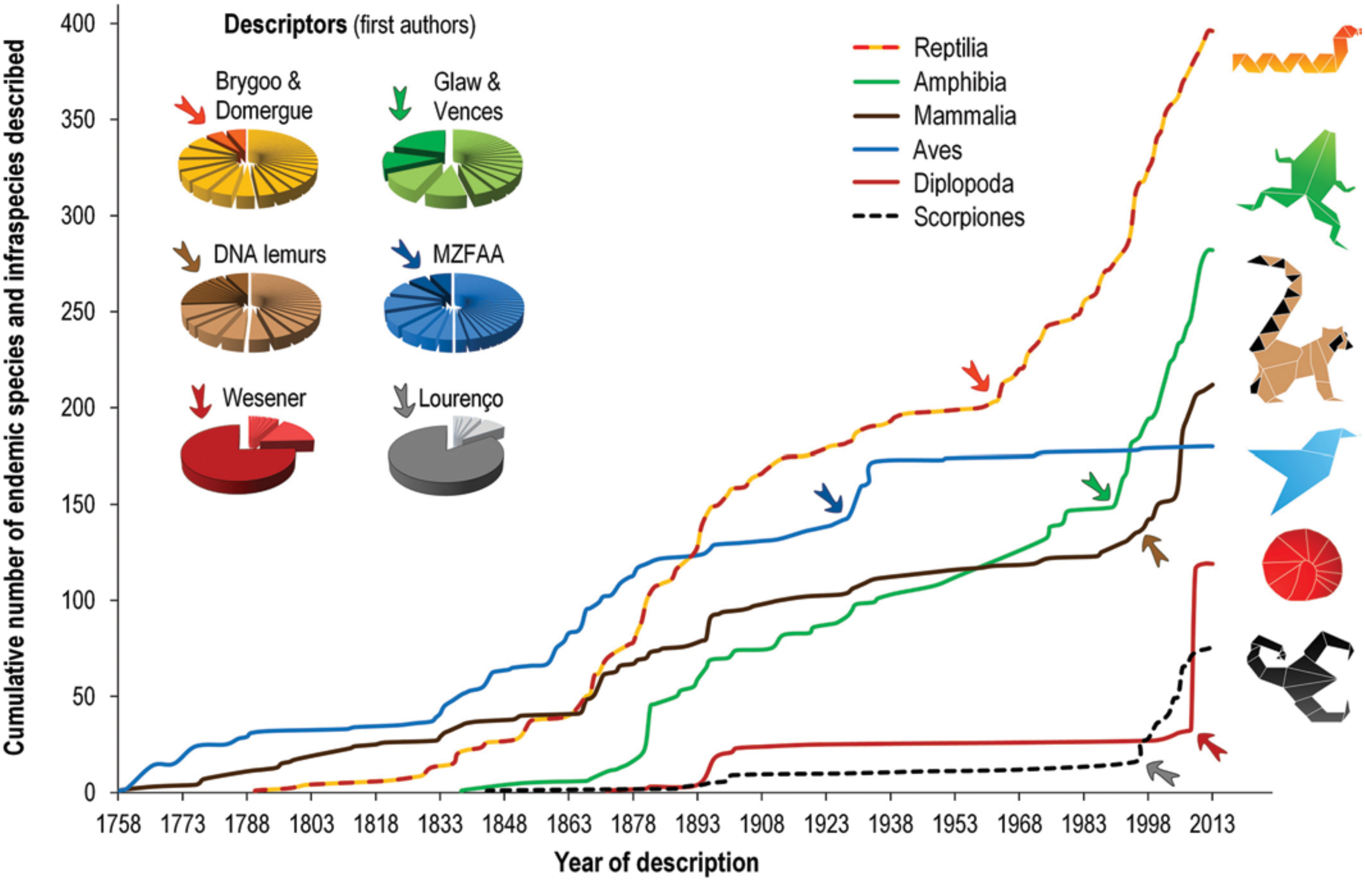


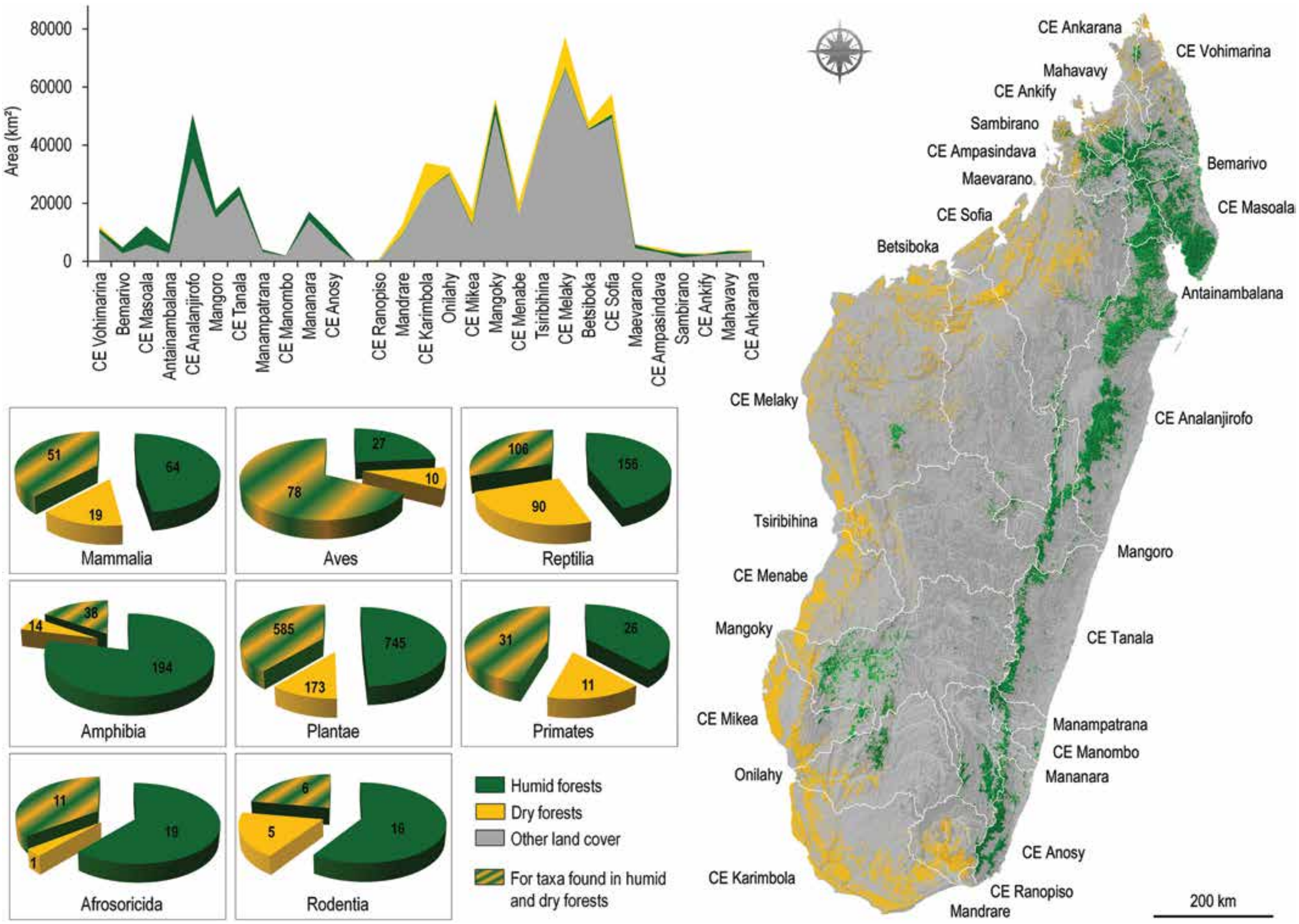
TABLE 2 *Sample description comparing dry and humid forests in Madagascar*

Group	Number of endemic forest species and subspecies considered	Number of records (one species or subspecies at a given locality and a given date)		
		Total	In dry forests	In humid forests
Vascular plants	1 503	28 169	7 762	20 407
Amphibians	246	2 717	341	2 376
Reptiles	352	4 241	1 878	2 363
Birds	115	15 605	4 695	10 910
Mammals	134	10 030	2 328	7 702

the dry forest as illustrated with some lizards: *Ebenavia maintimainty* Nussbaum & Raxworthy 1998 and *Paroedura maingoka* Nussbaum & Raxworthy 2000, only known within the Mahafaly calcareous Plateau or the *Zonosaurus bemaraha* Raselimanana, Raxworthy & Nussbaum 2000, only known from Bemaraha National Park.

Many species have recently disappeared from the dry forests, including forest mammals like giant lemurs or smaller mammals within the Afrosoricida or Rodentia as documented by subfossil records (e.g., Buckley 2013, Burney *et al.* 2008, Goodman *et al.* 2007, Mein *et al.* 2010). Dry event at ca. 4 000 years BP, plus human arrival (Gommery *et al.* 2011, Dewar *et al.* 2013) and further anthropogenic landscape changes (e.g., fire, Burney *et al.* 2004, Lowry *et al.* 1997) may have limited the less mobile groups to re-colonize the once wetter forests. However, only sedimentary rocks are able to conserve fossil and subfossil material that is destroyed in other rock types. Therefore, the fossil records are mainly distributed in the western sedimentary layers (Figure 1), and some paleolakes on the highlands (Waeber *et al.* in press), but there is almost no fossil known from places nowadays harbouring humid or subhumid forests (Muldoon *et al.* 2012).

FIGURE 3 *Forest cover in centers of endemism (CE) and in watersheds with high headwaters (Mercier and Wilmé 2013, Wilmé* et al. *2006, 2012) (top left). Dry forest versus humid and sub-humid species richness of endemic forest birds, mammals and plants (bottom left). Forest cover according to Moat and Smith (2007) (right)*



CONSERVATION AND POLICY

Protected area networks in Madagascar

Madagascar has been considered as a conservation priority for decades; high species richness coupled with its uniqueness has motivated the creation of the first parks and reserves at the beginning of the 20th century. Between 1927 and 1997, 46 Protected Areas (PA) were designated, including Strict Nature Reserve (IUCN Category I), National Parks (IUCN Category II), and Special Reserves (IUCN Category IV) (Bruner *et al.* 2001, Rasoavahiny *et al.* 2008).

For more than a century, the main threat to biodiversity has been deforestation (Green and Sussman 1990) which motivated the creation of the protected areas as early as 1927 as well as the inclusion of many of the endemic forest species on the red lists by IUCN (e.g., Ravaloharimanitra *et al.* 2011). Madagascar ratified the Convention on Biological Diversity in 1995. In September 2003 the former president Marc Ravalomanana made a pledge to triple the coverage of Madagascar's protected areas to encompass at least 60 000 km^2. By 2008, just prior the 2009 political crisis, the design of the New Protected Areas (NPA) was well advanced in its biological, geographic and legal aspects (Rasoavahiny *et al.* 2008). In 2013, while the legal aspects could not have made a step forward given that IUCN would not be able to recognize new status for protected areas adopted by a transitional government, the technical and geographic aspects have been refined, including both, the Protected Areas and the so-called New Protected Areas (Rebioma 2013).

The dry forests and its biodiversity were poorly represented within the previous system of protected areas (PA) (Rakotomalala 2008, Raselimanana 2008b). The main parks and reserves on the western slope of the island were actually protected for their impressive landscapes such as for the *tsingy* or karstic limestones with impressive erosion encountered in the reserves of Bemaraha, Namoroka and Ankarana, or the sandstones typical for Isalo National Park.

The spiny forest ecosystem of southern Madagascar is a globally unique ecosystem and characterized by high biotic endemism. Due to its remoteness and climatically harsh conditions, it has long been outside the focus of conservation priorities. The region has suffered the highest deforestation rates of Madagascar, with more than 30% of the spiny forest lost between 1970 and 2000 (Harper *et al.* 2007, Brinkmann *et al.* 2014). The spiny forest of southern and southwestern Madagascar, between the Anosy Chains (eastern limit) and the river Mangoky (western limit) cover an area of about 66 120 km^2. The region is characterized by recurrent water shortage, pastoral land use, agriculture on marginal lands, strong traditions and customs, and the over-exploitation of essential resources from natural forest ecosystems.

The dry forests with an estimated area similar to the humid forests are less protected (27% versus 48%), while their coverage has been almost tripled with the NPA as compared to PA (Table 3). Dry forests lie mostly over sedimentary rocks on the western slopes of Madagascar. Most of the dry forests (77%) are encountered within the sedimentary basins, mainly above sandstones and sand (Table 4). While global estimates of 75 to 80% of the continental crusts are of sedimentary rocks, Madagascar has only 36% of its surface covered with these types of rocks (Table 4). The dry forests lying on limestones were the best protected forests within the PA (620 km^2, 17%), however, the NPA assures the formal protection of the dry forests according to various underlying lithology (Table 4).

Portions of the eastern and western spiny forests are within the National Parks of Andohahela (Parcel II), and Tsimanampetsotsa. Two Special Reserves (Cap Sainte Marie, Beza Mahafaly) and five New Protected Areas are included within the spiny forest: Mikea National Park, NPA PK 32, and NPA Amoron'ny Onilahy in the western part, NPA Ifotaka, NPA Ankodida in the eastern part. Despite the extraordinary local diversity and specificity of its biodiversity, several plant

TABLE 3 *Comparative area of dry forests and humid forests (Moat and Smith 2007) in Protected Areas (PA) and New Protected Areas (NPA)*

Land cover	Area (km^2)	Forest in protected areas (km^2)		
		PA	NPA	Total protected areas
Dry forests	52 040	4 740 (9%)	10 350 (20%)	15 090 (29%)
Humid forests	53 260	9 380 (18%)	15 160 (28%)	24 540 (46%)
Other types	485 840	6 870	19 380	26 250
Total	591 140	20 990 (4%)	44 890 (8%)	65 880 (11%)

TABLE 4 *Distribution of different dry forest types (Moat and Smith 2007) according to underlying sedimentary rocks (Besairie and Collignon 1971) and their representation in the system of protected areas. (PA= current Protected Areas, NPA= New Protected Areas) (Rebioma 2013)*

Lithology		Area (km^2) of dry forest types				Area (km^2) of dry forest protected	
Sedimentary	**Area (km^2)**	**W dry forest**	**SW dry spiny forest-thicket**	**SW coastal bushland**	**Total dry forests**	**PA**	**NPA**
Alluvium	29 300	2 230	590	10	2 820	70	640
Dunes	9 900	220	1 660	1 500	3 380	30	345
Conglomerates	23 250	2 230	520	0	2 750	130	185
Limestone	17 690	2 270	1370	30	3 660	620	525
Sand	36 510	6 570	4 540	60	11 160	1 060	3 240
Sandstone	58 170	5 520	3 250	40	8 810	370	2 360
Duripan & duricrust	850	0	390	70	460	20	60
Clay & marl	39 220	5 140	1 940	20	7 100	2 170	460
Subtotal sedimentary	**214 870 (36%)**	**24 180**	**14 260**	**1 730**	**40 140**	**4 470**	**7 815**
Non sedimentary	376 270	7 740	4 100	30	**11 900**	270	2 535
Total	**591 140**	**31 920**	**18 360**	**1 760**	**52 040**	**4 740**	**10 350**

and animal species are insufficiently represented or absent from the current protected area network, such as two narrow-ranged endemic mammals, one nocturnal primate *Microcebus berthae* Rasoloarison, Goodman and Ganzhorn 2002 and the threatened Giant jumping rat *Hypogeomys antimena* A. Grandidier 1869.

Governance

Out of about 15 million rural people, over 13 000 rural communities are living in or adjacent to forests (McConnell and Sweeney 2005), and depend to different extent on forest resources such as firewood, construction wood, and non-timber forest products. Customary land use systems have been evolving over a long time mainly based on slash-and-burn agricultural practices (in many parts of Madagascar called *tavy*, in western Madagascar called *hatsake*). These customary systems are distant to political rules and regulations at the national level and sometimes even contradicting (Evers *et al.* 2006, Muttenzer 2006, Réau 2002). Due to growing threats of natural forest resources, the government sought to establish national resource use policies, in particular in recent years (ante 2009) with great support from international conservation organizations (Corson 2008, Rabesahala Horning 2008, 2012). Based on the Malagasy Environmental Charter adopted in 1990, the World Bank initiated the National Environmental Action Plan (NEAP) in the early 1990s (Henkels 2001, Mercier 2006). During the period of the NEAP (1991–2007) there has been a strong push to accomplish forest conservation in Madagascar, as elsewhere in Africa (Agrawal and Ribot 1999, Ribot 2002), through the process of formal decentralization of forest resources management. The respective legal framework consists of various legal instruments (forest legislation (N. 97-017 as of 8 August 1997), environmental decrees like MECIE (*Mise en Compatibilité des Investissements avec l'Environnement,* N. 99-954 as of 15 December 1999), conservation decrees and regulations of resource exploitation such as the inter-ministerial act on mining activities in conservation zones (N. 19560/2004 among many more), all embodying the Environmental Charta's objective (Henkels 2001) though eventually having developed into a rather complex and partly inconsistent legal system (Borrini-Feyerabend and Dudley 2005, Mercier 2006). In particular the implementation of the NEAP is split into three phases that lasted from 1991 to 2008 initially setting off institutions for sustainable development and later with a focus on in-situ nature conservation and poverty alleviation. In-situ conservation is laid down in the protected area legislation *Code des Aires Protégées* (N. 848-05/N. 2001/05) legalized in 2003, revised in 2015 under *Refonte du Code des Aires Protégées* (N. 2015-005), and supplemented with updated environmental charter, *Charte de l'Environnement Malagasy actualisé* (N. 2015-003).

Next to these national regulations on resource use, the government declared a law in 1996 governing the community-based management of natural resources in order to foster decentralized structures in natural resources management and to formalize resource use at the local level (Rakotoson and Tanner 2006). Since 2001 the policy has been implemented locally by transferring management rights and responsibilities from the state forest agency to local communities, the so-called *Gestion Locale Sécurisée* (secure local management, GELOSE), 10 September 1996, law N. 96-025, and *Gestion Contractualisée des Forêts* (forest management contracts, GCF) especially considering public forests (Law N. 97-107 and Decree 97-1200) (Antona *et al.* 2004, Casse *et al.* 2004, Dressler *et al.* 2010, Raik and Decker 2007). Case studies lead in the areas of Ankikiky and Tolikisy, included in the southwest region of Madagascar, highlighted that management transfers remain superficial, despite the signing of contracts. Local residents accept it mainly for land interests while migrants (now a majority in the area) do not agree with it at all (Ramamonjisoa and Rabemananjara 2012).

In western Madagascar, all unprotected areas are under pressure and potentially targeted by land clearers; fires sometimes also encroach protected areas (Smith 1997). Further, mining projects oftentimes coincide with boundaries of protected areas (cf. Cardiff and Andriamanalina 2007). Despite the inter-ministerial orders N. 19560 of 18 October 2004, N. 17914 of 18 October 2006 and N. 18633 of 17 October 2008, regarding mining in protected sites or temporary protection areas, mining exploration sites still exist within the created NPA (but see also Figure 4). Additionally, Article 250 of the new mining code sets out a particular emphasis on operating ban within a conservation area. However, between the orders N. 17914 of 18 October 2006, and N. 18633 of 17 October 2008, a large number of exploration and exploitation licenses have still been issued (Soanirinavalona 2009). In 2010, a new organizational regulation of the charcoal industry based on the application of the regional order was implemented in the southwest. The order is accompanied by various implementing regulations at the level of administration, municipalities and *fokontany* (community) such as regulatory note, municipal decree and *dina* (a locally developed and applicable agreement or local law). To answer pressures on the dry forests, systems of co-management based on participatory approaches with community associations are under development. During the last 15 years conservation institutions (e.g., Madagascar National Parks, WWF, GIZ, Conservation International, Tany Meva, Small Grant Programme) and development NGOs have focused their activities in the region. In the Mahafaly, several conservation projects embracing these concepts have been implemented (co-management of forest resources, research program on sustainable land management, and support for extension and management of Tsimanampetsotsa National Park). As a result, 320 000 ha, i.e., 20% of the area has been transferred to 38 local community managers (called *communautés de base Vondron'Olona Ifotony* (VOI)). Tsimanampetsotsa National Park, the core zone of this conservation area, covers 12% of the total area and is managed by Madagascar National Parks, the national institution responsible of protected areas in Madagascar. Rural development has been incorporated into all projects in the Mahafaly to maintain biodiversity through the reduction of anthropogenic pressures on natural resources.

DRIVERS OF CHANGE

In this section the focus is on the current proximate causes and underlying drivers of change (Geist and Lambin 2002) to dry forest cover in western Madagascar. Issues such as economic factors, from regional to international scale, exchange rates, and development projects are driving the practice of forest clearance and degradation (Hufty and Muttenzer 2002, Kull 2000). An increasing human population and a constantly growing need for more land are probably the biggest driver of change and represent the major pressure to forests in the west of Madagascar. Poverty, often used to explain deforestation (cf. Lambin *et al*. 2001) does not always drive deforestation or land conversion to crop fields, it is the farmers' rationality based on economic and agronomic logic that pushes to transform the land to be of better use to them (Kull 2000). However, the government and conservation NGOs in established discourse blame rural households to practice slash-and-burn (Laurent 1996, Favre 1996), while this practice contributes intensively to the alimentary and financial safety of the population (Urech 2012). From the point of view of the Sakalava (Menabe), these practices are also a way to preserve soil fertility as long as traditional rules are respected (Scales 2012), and in turn they blame migrant communities for unsustainable slash-and-burn practices. Often, maize is responsible for deforestation and migration. In the following five subsections, the main drivers are listed from currently most important to potentially becoming bigger drivers of change in the future in a western Madagascar context.

Agriculture

Subsistence agriculture is described a prime driver of deforestation in Madagascar (Green and Sussman 1990, Milleville and Blanc-Pamard 2001, Sussman *et al.* 1994, Whitehurst *et al.* 2009). While slash-and-burn agriculture, *hatsake*, is still the traditional and predominant land use practice in forested regions everywhere in Madagascar (Styger *et al.* 2007), it has been singled out as the major cause of recent deforestation along the west coast (Genini 1996), where it is practiced to grow maize. Maize production in the west accounts for approximately 80% of the agricultural land; it represents a fast forward and effective production system, guaranteeing fast cash returns. Maize production does not require specific farming skills, and the crop responds well to degraded soils and produces relatively high outputs (Réau 2002).

Hatsake is used to clear and remove the woody biomass. Slash-and-burn agriculture is considered a sustainable land use system under conditions of abundant land availability and low population density (Kleinman *et al.* 1995) and when selective slash-and-burn is practiced (Carrière 2003). However, when these conditions are not fulfilled, soils cannot recover their fertility before being re-cultivated (Van Noordwijk 2002).

As in other slash-and-burn systems, the burning produces ash which recycles nutrients and makes them available for crop growth (Raharimalala *et al.* 2010). No farming maintenance is required (cf. Genini 1996 for details on maize farming in western Madagascar); yields can reach two tons in the first year (Genini 1996); fields of the first year are called *hatsababo* (Ottino 1963). After each maize crop cycle, the yield starts to decline, and after about four years, it is below 80% of the *hatsababo's* (Réau 2002). The fields of the second and third year give the name of the *hatsake* (Ottino 1963). Before abandoning these fields, they are cultivated with less productive groundnuts, cassava, or sweet potatoes.

Repeated clearings lead to a change in the vegetation so that land will be converted to open grassland with a low potential for cultivation (Milleville *et al.* 2000). Soil-vegetation patterns in secondary slash-and-burn succession in Central Menabe suggest that only *monkas* which have been abandoned for twenty years or more recover enough fertility to be re-used as agricultural land (Raharimalala *et al.* 2010, 2012).

Maize, however, is not only grown for subsistence purpose. Several thousand tons of Malagasy maize is exported annually to Mauritius, the Seychelles, and to Reunion; to the latter mainly for pig feed especially since the 1990s (Réau 2002).

Charcoal

Like many countries in Sub-Saharan Africa, Madagascar is still highly dependent on wood biomass for domestic energy supply. For many cities located on the west coast, the raw materials used in the manufacture of charcoal come mainly from dry and spiny forests (Dirac *et al*. 2006). For the city of Toliara located in the southwest, firewood production is entirely provided by the dry natural forests. This urban area is supplied by four areas: the *Route Nationale* RN7 provides 33% of the charcoal, while 53% comes from the RN9, 10% from the Miary axis, and 4% from the RN10 (PARTAGE 2011). The amount of charcoal entering the city is estimated at 34 860 tons in 2012. The diagnostics on firewood conducted in 2012 showed that the region's resources will no longer be able to satisfy the demand from 2030 (WWF 2012).

Zebu

In western Madagascar, forests also serve as pastures for livestock. With the rise of cattle theft and growing insecurity, people also keep their cattle inside the forest. This contributes substantially to the degradation of the forest and puts pressure on recruitment (Ratovonamana *et al*. 2013). Forests, open woodlands, grasslands and *monkas* are also burned to produce fresh pastures for zebu. Burning favors the regeneration of herbs that is used as fodder for zebus while removing lignified grass (Kull 2002, Réau 2002). Zebu cattle (*Bos indicus* (Linnaeus 1758)) were introduced to Madagascar probably from mainland Africa around the eleventh century (Gade 1996). Last century, the number of zebus surpassed human inhabitants in the island (Kaufmann and Tsirahamba 2006). In 2000, the World Bank (2003) estimated that the total population of 7.5 million zebus impacted over 50% of the entire landmass of Madagascar. In western Madagascar, zebu herding is a prevalent and culturally embedded reality

(Réau 2002). In the Mahafaly (southwest), zebu farming acts as banking system, where the zebu is like assets in a bank, and the land (forest, pastures) is perceived as a banking infrastructure (Clutton-Brock 1989, Kaufmann and Tsirahamba 2006). Zebus also have a critical ritual and symbolic value: they are used to appease spirits, to overcome times of famines, or as bridal gifts (Kaufmann and Tsirahamba 2006). Réau (2002) illuminated the linkage between maize, zebu and deforestation in his article "burning for zebu", using the example of the Tandroy migrants from the Androy (southern Madagascar) in the Menabe (west Madagascar). The extreme poverty of the Androy region forces many of its inhabitants to migrate to western Madagascar in search for land. Forests are cleared to stake a claim on land since forests are seen as common property and open-access resource by the Tandroy (Andrés-Domenech *et al.* 2011), which at later stage is been used to accumulate zebus ("turning the forest into zebu", Réau 2002: 225). The bigger the zebu herd the higher social status for a Tandroy back home can be achieved. Once a forest patch is cleared, maize will be produced more for export rather than subsistence. The money can then be invested into zebu acquisition; for instance Réau noted in 2002 that one hectare of maize on *hatsabao* land allows a Tandroy to invest in 1.3 zebus. With the cultural and social pressures the Tandroy's practices of *hatsake* constitutes hence further pressure on the dry forests of the west. In their own land of Androy, forest covers have already been reduced from 30% in the 1960s (Humbert and Cours-Darne 1965) to less than 23% in the 2000s (Andrés-Domenech *et al.* 2011).

Mining and other extractive industries

While in 2003 the former President Ravalomanana in the Durban Declaration stated to triple the protected areas in Madagascar by putting about 10% of Madagascar's surface aside for conservation (Norris 2006), he concurrently opened up the country to foreign investments to increase the country's development and to fight poverty; Madagascar is not only rich in biodiversity but also rich in minerals and oil deposits (cf. Raharimahefa 2012). Here three types of investments are briefly presented: 1) extractive mining industries, 2) extractive oil industry, and 3) agribusiness industries. They all share the common potential for high environmental and social risks, while bringing Malagasy legal authorities much needed cash.

Large-scale mining contracts have been issued, with the two most prominent being Rio Tinto/QMM ilmenite mine in Fort Dauphin, southeast Madagascar (Evers and Seagle 2012, Seagle 2012, 2013), and Sherritt International nickel mine in Ambatovy, near Moramanga (Cardiff and Andriamanalina 2007, Evers and Seagle 2012). In western Madagascar, similar projects are underway constituting a competition for land with local stakeholders but also a threat to forested systems. The conflicting land uses of three government-sponsored projects in the Mikea area, Toliara-Morombe region (establishment of the Mikea National Park, ilmenite mining, oil exploration, all with overlapping borders) destabilized local populations, mainly affecting the autochthonous Mikea during the boundary negotiation phase 2007–2009 (Huff 2012) who have been encouraged by the government to preserve the forest (Blanc-Pamard 2009). In this region, the Australian company Ticor Limited in a joint venture with the South African Kumba Resources Ltd are prospecting for ilmenite mining in the Mikea. Exploration Madagascar, a subsidiary of World Titanium Resources Ltd (WTR) who holds a partnership agreement with Ticor, owns the exploration permits for the area (Blanc-Pamard 2009). WTR also owns the Ranobe Mine Project (between the Fiherenana and Manombo rivers), which entails the Ranobe mineral sand deposit and zones of mineralized sand to the north (cf. Martin and de Wet 2012). This mining project is affecting southwestern dry spiny forest-thicket (exploitation zone and haul routes) and southwestern coastal bushland (haul routes).

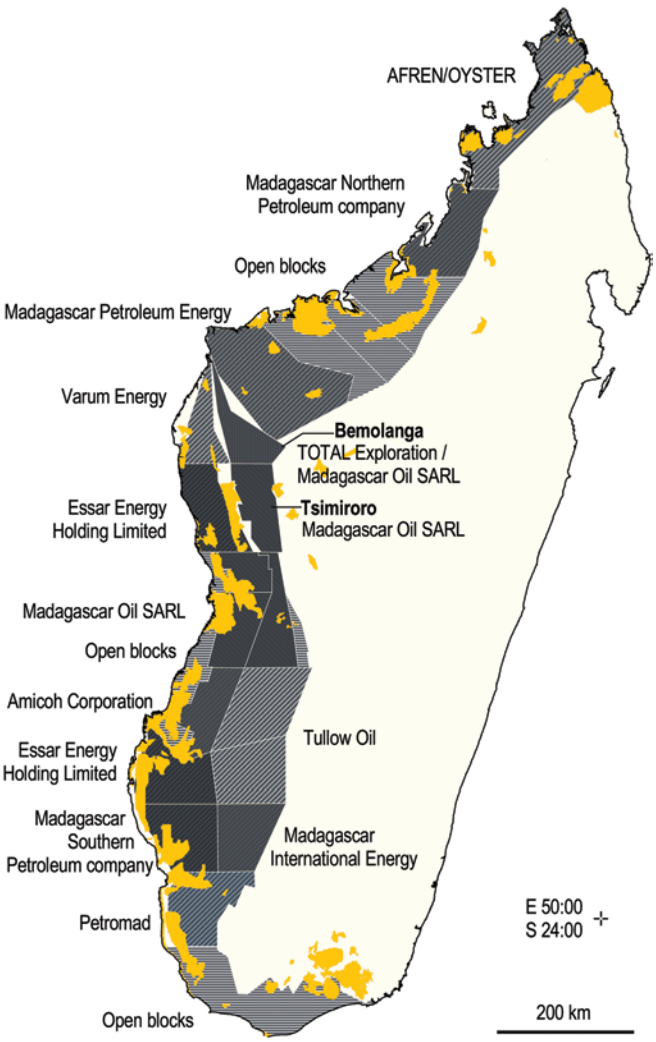
Two important oil fields, Bemolanga and Tsimiroro, have drawn the international attention of many oil companies. *Office des Mines Nationales et des Industries Stratégiques* (OMNIS), founded in 1976, is today partnering with an array of internationally active and important companies (e.g., Agip, ExxonMobil, Shell, Sterling Energy, Triton). According to OMNIS (2014a), the entire west slope with underlying sedimentary rocks has been granted for on- and offshore oil well exploration (in total 75); many onshore exploration wells coincide with forested areas and most protected areas, Bemaraha National Park being the only exception (Figure 4). This constitutes a particular concern and potentially represents the biggest threat to the remaining forest systems in the west of Madagascar.

In November 2008 international news media brought Madagascar to the centre of attention: Daewoo Logistics, a South Korean company, is in negotiations with the Malagasy government for the transfer of 1 300 000 hectares of arable land in four coastal regions. The then political opposition of President Ravalomanana's regime used this large-scale land deal to accuse the Ravalomanana regime of selling off the nation's heritage to foreigners (Teyssier *et al.* 2010); the *coup d'état* followed a few months later (Randrianja 2012a, 2012b). Despite these events, state representatives and local elites generally welcome agribusiness investments; 52 agribusiness projects have been announced between 2005 and 2010, but one third did not pass the prospecting phase or has stopped concerning an area of roughly 150 000 ha; the majority of these investors are Europeans, the others Malagasy (Andrianirina-Ratsialonana *et al.* 2011). The majority of agribusiness projects aim at the production of biofuels (e.g., jatropha), and are in the scale of 10 000–30 000 ha (ibid). Agribusiness is targeting areas that are flat, easily accessible (by road), and that are in vicinity of ports for exports (in bref, these are the conditions found in western Madagascar).

Climate

Temperatures in southern Madagascar have been in steady ascent in the past 50 years, being approximately 0.2°C warmer than compared to before 1950s; in contrast, precipitation is less than 40mm per average month over the past century in southern and western Madagascar (Tadross *et al.* 2008).

FIGURE 4 *Oil exploration area on sedimentary rocks (dark) as described by OMNIS (2014a) with Protected Areas and New Protected Areas (yellow) holding dry forests*



Interestingly, also farmers have recognized changes in recent climate; they have started to shift from the Malagasy staple crop rice, which cultivation requires a lot of water, to rain fed crops such as maize, groundnuts and others since in the past 50 years a change in precipitation has led to the drying out of some rivers in the Menabe region (Tache 1994, in Raharimalala *et al.* 2010). These crops are based on slash-and-burn production of forests. Changing climate not only affects temperature and precipitation levels; it also affects intensity and frequency of extreme events such as droughts or fires (Dale *et al.* 2001). Latest global models project a decrease in the frequency of cyclones, but an increase of intensity; the frequency of the most intense cyclones, however, is also projected to increase (Knutson *et al.* 2010). Between 1961 and the year 2000, 62 cyclones passed Madagascar, of which some 50% affected dry forests, mainly in the Mahajanga region (Service Météorologique Madagascar, unpubl. report). Current cyclone season starts in November and lasts until April. Climate modelling research projects for Madagascar are rare. Tadross *et al.* (2008) projected fewer cyclones over the southwest Indian Ocean, but with increased Potential Intensity of between 2–17%. Impacts of cyclones are also little studied in Madagascar (e.g., Birkinshaw and Randrianjanahary 2007, Rasamimanana *et al.* 2000, Ratsimbazafy *et al.* 2002). Lewis and Bannar-Martin (2012) assessed the impacts of Cyclone Fanele on dry forests and their findings fit with Lugo's (2008) global review: Cyclones have a negative impact on forest structure, composition and biomass. However, a cyclone by itself has less impact on the forest ecology than people using the new openings to enter the forest and cut trees afterwards (Ganzhorn 1995).

To gain a better understanding of these drivers it is crucial to have a look back in the past. Agricultural production in west Madagascar has been introduced by the French colonialists in the early 20th century (Scales 2011) leading to social and economic transformations (Réau 2002). Three agricultural booms in western Madagascar followed each other: Rice cultivation, butter beans (*Phaseolus lunatus* L. 1753), and maize cultivation. In the early 20th century, the colonial authorities improved infrastructures to increase the rice cultivation based on irrigation. Within 20 years more than 40 000 ha of land have been converted into rice paddies in Central Menabe, which was granted to mainly expatriates and the Malagasy elites' concessions, leaving the local Sakalava, the traditional pastoralists on the margins (Scales 2011). The butter beans boom (the production not being constraint to irrigation systems) took place between the Morondava and Tsiribihina rivers. Large concessions were in need of labour attracting people mainly from Madagascar's southern regions. Another reason for migration is linked with the extinction of the *Opuntia* spp. across the entire south. The colonial power introduced a cochineal insect in the early 1920s to reduce the number of *Opuntia,* perceived as the true symbol of local resistance against the new power. Within five years all plants had been wiped out, with dramatic consequences; deprived of their entire livelihood base, several hundred or thousand people, and some 10 000–300 000 zebu died in total (cf. Middleton 1999, and references therein). This forced an unknown but high number of people to leave the region and migrate westwards in desperation to find better life conditions elsewhere (ibid). Additionally, several drought spells in southern Madagascar (cf. Virah-Sawmy 2009) in the past 50 years have caused scarcity of water and food leading to more famines; consequently new migration waves into west Madagascar took place. This may have reduced the pressure on the southern forests, in that fewer people were there to use the forests, so they potentially could recover (Virah-Sawmy 2009); however, the migrating people cause increased pressures in western dry forests. Deforestation in such a context is often further accentuated at borders of territories or between communities; basically on land where the tenure system is unclear or uncertain (Durbin *et al.* 2003). Severe droughts in southern Madagascar have been reported since the beginning of the 20th century but may have become more regular since the severe drought in 1981 and an increase in frequency since 1988. In the driest regions of southern Madagascar where drought occurred in recent years, it has been noted that less forests have been cleared for access to land during periods of drought while the pressure on other forest services has increased to allow people to generate some income (Casse *et al*. 2004, Elmqvist *et al*. 2007).

DISCUSSION

Biodiversity

The tropical paradigm as well as the high diversity encountered in some groups of plants or animals within the humid forests are casting a shadow over the dry forests; there is comparatively little published when relating the actual endemism of dry forests to humid forests. In Madagascar, the main pattern recognized for most groups of living organisms is the opposition West versus East, usually understood as dry forests opposed to humid forests. In many groups, including birds and mammals, many small-ranged species contribute to the species richness. The narrow ranges of many of these species are best explained by the centres of endemism (Ganzhorn *et al.* 2014, Mercier and Wilmé 2013, Wilmé *et al.* 2006, 2012) while other evolutionary processes certainly contribute to species diversification (Vences *et al*. 2009 and references therein). When considering the distribution pattern of the forest mammals, birds, reptiles, amphibians and plants the dry forest avifauna stands out. The plants, mammals and amphibians clearly show a higher richness in the humid forests, while the species richness for birds is almost as important in dry forests as in humid forests (Figure 3, Raherilalao and Wilmé 2008).

Previous analyses with the same botanical sample as used in this study has shown that the main roads are an important bias (13% of the specimens have been collected within 2.5 km from a main road), as well as the two main mining sites near Fort-Dauphin in the southeast, and at Ambatovy in the east. The western dry forests and to a lesser extent the spiny thickets and bushland, are extremely challenging to access during the rain season or after occasional rains. The biological collections and studies usually take place during the breeding or flowering season which is also the rain season. The humid forests are not as difficult to access during the rain season, and the surveys are thus facilitated in the humid biomes, which may partly explain the underrepresentation of the western samples in the collection and references.

Fire as an agent, but not a driver of change

Fire is an important ecological process and management tool in Madagascar's dry forests. It can be the proximate cause for forest loss, but also a means to shape particular vegetation outcomes (Ehrensperger *et al.* 2013). Fire's role in the dry forests is diverse. First, the frequency, timing, and severity of burning affect outcomes: For instance, Pons and Wendenburg (2005), working in the Ankarafantsika forest, show that avian conservation values are higher in a recently burnt forest versus an unburnt forest, but that open grasslands resulting from repeated heavy burning have lower avian conservation value.

Second, fire impacts vary in relation to the ecological characteristics of particular forest types, including fuel load and structure, seasonality of rainfall, fire adaptations of the vegetation and fauna, and phenologic growth stage of different plants (Bloesch 1999). Impacts of fire vary by target species: One species of *Coua* Schinz 1821 (a terrestrial bird) benefits from fire, while another does not (Chouteau 2007). In the open grasslands of Sakaraha, regular fires reduce phytomass but increase floristic diversity (Rakotoarimanana *et al.* 2001).

Third, fire's role also varies based on the socio-economic characteristics of land use in particular geographic regions. Different kinds of fire help or hinder particular land management goals. Among people who practice subsistence foraging, like the Mikea, fire may help to maintain certain vegetation types or locate wild yam (*Dioscorea* L. 1753) species (Bloesch 1999). For zebu cattle pastoralism in grasslands and adjacent forests, annual fires serve to reduce fuel load, prevent bush encroachment, and remove unpalatable lignified stems (Kull 2004). In the maize frontier north of Toliara, fire serves to clear forest and establish crop fields for subsistence and market demands (Blanc-Pamard 2002).

Fire policy at the national level has rarely engaged with fire at the detailed level necessary – specific to local ecological characteristics and forms of land uses (Kull 2004). It has tended to one-size-fits-all policy. Furthermore, little research exists, at this point, about the possible use of fire in managing protected areas and classified forests for purposes of conservation or forestry. Clearly, fires as a tool for land conversion from dry forests to maize plots require different approaches than annual pasture fires or inevitable wildfires in forest areas. The former are a manifestation of demographic and economic development pressures; the latter are phenomena of land and conservation management.

From local agricultural needs to globally driven interests

Secondary forests are the result of natural and/or anthropogenic disturbances. Succession is determined by the availability of propagules (Turner 1989), the disturbance history (Pickett and White 1985), climate and topography, and is modified by climate change and invasive species (Brown and Lugo 1990, Chapin *et al*. 2000). Fire initiates a predictable vegetation succession that can lead to open grasslands in its ultimate stage of degradation (Lowry *et al.* 1997, Milleville *et al.* 2001). Moreover, soil impoverishment is characterized by increased erosion, soil compaction and higher evapotranspiration (ibid). According to Grouzis *et al.* (2001) this practice leads to a permanent loss of dry forests. Abandoned fields, or *monkas*, are repopulated by woody species replacing the herbaceous layers after about 20 years. This goes along with soil recovery and maturation and would potentially allow for a 20-year rotation cycle (Raharimalala *et al.* 2010). Farmers instead, often re-use secondary lands or open up new fields slash-burning natural forests. A reason for this could be that also farmers start to realize that a "saturation of space" could soon become an issue (Blanc-Pamard (2009: 9). Forest land in Madagascar belongs to the State who is entitled to sell it. In contrast, according to common law, land belongs to the ones who clear it (Réau 2003). "The right of the axe" (Blanc-Pamard 2009: 5), i.e., the clearer and his descendants can hold the land as long as they use it. Policy mechanisms like the CGF and GELOSE initiatives shift land tenure from land property to land holding. Land holders cannot sell it, but the land can be inherited (Raharimalala *et al.* 2010).

Potentially a bigger scaled threat for dry forests is represented by the oil extracting industry. Currently, in the entire west of Madagascar, explorations for oil are ongoing and coincide with large plots of forested area. Once an exploration phase has turned into an issued permit, there is potentially a lot of infrastructure to be put in place for the actual extraction and transportation of the natural resources. Pipelines and road network, what Laurence *et al.* (2009) call "linear clearings" will add further to forest degradation and fragmentation (ibid). In Madagascar, all mining and petroleum exploitations are subject to prior environmental impact assessment, and are governed and described in the Environmental Charter (*Mise en Compatibilité des Investissements avec l'Environnement* MECIE) to ensure the "promotion of ecological and social equilibrium" (OMNIS 2014b). To reduce rates of biodiversity loss and environmental impacts by mining activities, mining companies are marketing a *no net loss* of biodiversity, or a *net positive impact* following destructive activities (Rainey *et al.* 2015, ten Kate and Inbar 2008). Regulations are in place and best practices, following the mitigation hierarchy of avoiding, minimizing, restoring, offsetting to achieve these goals are formulated by the BBOP (Business and Biodiversity Offsets Programme), an international collaboration between companies of the extractive industries, financial institutions, government and non-governmental agencies (BBOP 2013). Biodiversity offsetting seems to be coming into vogue in Madagascar, and bears the risks to unload and shoulder forest degradation and environmental destruction on farmers' traditional behaviour rather than on the destructive extraction practices (cf. Waeber 2012, and references therein).

Another important pressure on Madagascar's lands is represented by agribusiness. Land transfers for lease or purchase for agriproduction oftentimes undermines local land rights and access (Daniel 2011, Deininger *et al.* 2011). New land policies have been implemented in Madagascar that govern land tenure and right, where in a first step the old colonial assumption of "land belongs to the state" has made space for a decentralization approach to local governments (Teyssier *et al*. 2009, 2010). Besides these changes, there is still room for violation and profit making to the cost of local and traditional landholders. Burnord *et al.* (2013) present three case studies from west and northern Madagascar that show how the different state representatives (central and regional governments) and local elites or different ethnic groups (e.g., Betsileo rice cultivators versus Sakalava cattle breeders) compete amongst themselves and between respective stakeholders over the corresponding benefits and over land management more generally, making agri-investments processes difficult, and especially less transparent. It is with such case studies where research can put its leverage and try to engage with the various and potentially conflicting parties to engage in participatory approaches (e.g., Garcia *et al*. in press) to collectively develop and test scenarios to better inform the various parties involved, but ultimately to propagate bottom-up produced knowledge and understanding that reaches and engages the policy and decision makers.

Addressing complexity

Livelihood-based research is required to highlight the direct contribution of dry forests in Madagascar to subsistence economy. This discipline needs to be linked with the food production potential that western Madagascar represents for national but also for international markets. It is unclear to what extend for example maize production in western Madagascar is intended for subsistence only and how much is based on industrial or export production. These linkages are crucial to understand and address drivers of change where local and global needs and dynamics meet (Cash and Moser 2000, Millennium Ecosystem Assessment 2005).

As highlighted by Blackie *et al*. (2014), what accounts for the global scale, holds true also for Madagascar: research on sustainable management of dry forests is likely the biggest gap to date. In the dry forest socio-ecological systems (sensu von Heland and Folke (2014), and references therein), as seen in this study, drivers of forest change are linked to various stakeholders with different value systems and agendas. Some are indigenous people (such as the Mikea), or local people, or migrants from other regions of Madagascar in need to seek a living mainly through working the land or herding cattle; some were external stakeholders such as the colonialists having promoted agricultural production at bigger scales to satisfy mainly European markets and spurring migration within Madagascar; some are just about to start exploring the natural riches of the dry forest system for global markets of oil and minerals (and again, these stakeholders may promote more migration into the west as seen by the colonialists), others are representing international companies interested in using the land for agribusiness (Franchi *et al*. 2013, Neimark 2013). Local and global energy demands show also high potential of conflicts especially around territorial boundaries (Mulder *et al.* 2010, Muttenzer 2012, Ramamonjisoa and Rabemananjara 2012). Forestry policy scenarios are required that allow for sectoral and especially cross-sectoral analyses that are transboundary in nature, to better allow for the conservation of dry forests, its endemic fauna and flora, but also allow to address the increasing energy demands deriving from different scales.

The majority of research and literature reported here is based on disciplinary approaches; this has been crucial to accumulate and create scientifically based knowledge and understanding on the various components of dry forests in Madagascar; local knowledge studies, though significantly less in numbers, have complemented the information and understanding process. In recent years, inter- and transdisciplinary projects such as the SuLaMa (Sustainable Land Management in south-western Madagascar, e.g., Plugge *et al*. 2014) in the Mahafaly region are using a landscape-based approach (cf. Sayer *et al*. 2013) engaging many different stakeholders, seeking to strike a balance between conservation of the biodiversity values and agricultural production. Such holistic approaches have the best chance to address complexity and deal with the inherent wicked problems (sensu Rittel and Webber 1973) that management and decision makers have to deal with.

CONCLUSION

The dry forests in Madagascar have clearly been neglected by conservation and research activities compared to humid forests. The latter show higher species richness and diversity, while the dry systems host important biodiversity, including narrow-ranged endemic taxa. More disciplinary research is likely to increase the number of new species, especially for plants. Deforestation in Madagascar has long been depicted as the main environmental issue, for humid and dry forests. Farmers have too often and easily been blamed as the main culprits for environmental degradation due to their widely used slash-and-burn practices. However, in water deprived regions such as the west and southwest of Madagascar, where farmers are to change their strategies to less water dependent crops because they experience and understand the water scarcity, extractive industries in contrast seem to be on the rise and ignoring the water situation; this represents a substantial threat to the dry forests nowadays, but in line with a global trend of water shortages (Mulder *et al*. 2010). This stakeholder is not only changing the landscape through increasing deforestation and fragmentation, it also requires water for any kind of extractive activity. This will further accentuate the pressures on an already dry environment, with a climate that shows trends of increasing temperatures and reduced precipitations, as observed in the past 50 years.

With a steadily growing population, available land for agriculture is getting scarcer, and pressure on the remaining forests is increasing. Food and energy security are on the global radar. As long as fundamental needs are not addressed properly, people will struggle for their livelihood and biodiversity will further deplete. The Malagasy government is faced with the challenge of balancing the interests of its citizens which is often in opposition with those of the international communities.

Research approaches are needed in taking a holistic approach, with many different scales in scope; looking at socio-ecological systems allows to gain an understanding of system actors (e.g., fire), drivers (e.g., climate change), and feedback loops. This allows the development of livelihood and governance scenarios to better address the ongoing rush for land, to test and consider new agricultural techniques, and to balance food security and conservation needs. Management of the natural resources in western Madagascar is crucial, especially forests that serve as a base for biodiversity and ecosystem services. Water will be key in future management planning, not simply rainfall or cyclones, but water availability for the wildlife, people, and the economy.

Madagascar is culturally diverse, and a grand portion of the population still lives according to traditional norms and rules, while especially the national governing bodies follow a different value system. Research can create knowledge and understanding of complex and diverse systems, where many different stakeholders have different agendas and interests. This information can and need to be translated into tangible actions to support the governance system to have more flexible policy frameworks. A one-size fits all policy is not helpful, especially where local rules and norms are still prevailing. Governments need to be provided with scientifically based tools that allow to balancing best future needs to carefully weigh the protection of its natural resources versus the investments and benefits from the utility of such limited resources, especially in regions where extreme environmental conditions are slowing down the regeneration of important resources.

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