Monitoring land cover changes in African protected areas in the 21st century

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A B S T R A C T

Africa is home to some of the most vulnerable natural ecosystems and species on the planet. Around 7000 protected areas seek to safeguard the continent’s rich biodiversity, but many of them face increasing management challenges. Human disturbances permeating into the parks directly and indirectly affect the ecological functioning and integrity of protected areas. With the envisaged expansion of the protected area network and further expected population and economic growth in the region, the competition between nature conservation and resources demands is likely to increase. The regular monitoring of land cover in and around protected areas can support the early detection of conservation conflicts. In this paper, we evaluate the use of the annual time series of MODIS Land Cover (LC) type product between 2003 and 2009 to monitor land cover changes at continental scale. We use the mean classification confidence and change frequency as indicators to assess the temporal consistency of the MODIS LC classifier for accurately monitoring land cover changes. We discuss the perspectives and issues for an automated monitoring of land cover changes in African protected areas.

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1. Introduction

Protected areas have become key elements of national and international conservation strategies to preserve biodiversity and natural systems (Dudley, 2008). Rapid population growth coupled with an increasing demand for food, shelter and income over the last century have lead to the increased ecological isolation of protected areas (DeFries et al., 2005). In Africa, this trend has been exacerbated by large-scale land use changes financed by foreign and local capitals interested in the extraction of natural resources and the production of agricultural crops for international markets (Cotula et al., 2009; Hilson and Haselip, 2004; Velpaala and Ali, 2005). Often, the effects of landscape transformations do not halt at park boundaries, but permeate into the protected lands (Bruner et al., 2001; Laurance et al., 2012). This affects directly or indirectly species behaviour, abundance and composition, as well as ecosystem processes (Craigie et al., 2010; Laurance et al., 2012). Direct human activities within the park, such as harvesting of wild plants and animals, as well as logging, agriculture and livestock herding, increase when an inadequate park design and administration disregards the needs of local populations to sustain their livelihoods (Naughton-Treves et al., 2005), or when a lack of funding or civil conflicts hinder an effective park management (Blom et al., 2004; de Merode et al., 2007; Plumptre et al., 2001). With the further envisaged expansion of the protected area network (CBD/COP-10, 2011) and the further expected population and economic growth, the competition between nature conservation and resource demands is likely to increase (e.g., Prins, 1992; Rondinini et al., 2006).

Extensive assessments and monitoring tools are being set up to survey the biological conditions and pressures at protected areas (Dubois et al., 2011; Laurance et al., 2012; Mulligan, 2008; Young et al., 2009). The overall aim is to assess the effectiveness of protected areas in progressing towards defined conservation objectives allowing to adapt conservation actions and to identify priority areas. The more frequent these assessments can be done, the earlier conservation conflicts can be detected. This task is ambitious, especially when a large number of protected areas are frequently surveyed. The automation of the monitoring is therefore desirable. Remote sensing and the mapping of land cover/change can facilitate this task. Over the last 40 years, remote sensing has become an efficient and cost-effective tool for repeated monitoring of land cover over large and often remote areas (Groen et al., 2011; Lambin and Geist, 2006). Despite these advances, the mapping of land cover changes over large areas remains a challenge (Achard et al., 2002). Much of the change detection process remains difficult to automate without user input, and is therefore costly in terms of time and resources (Achard et al., 2009; Young et al., 2009). Time series of coarse resolution satellite products, like MODIS Vegetation Continuous Fields (VCT) and MODIS Land Cover (LC), have the potential to facilitate the generation of repeatable and consistent results. Even though these products are low in spatial resolution (500 m), they have the advantage to be readily available. They provide easy means to screen protected areas for major land cover changes by...
simply comparing successive years. Once hotspots of changes have been identified, assessments can focus on these areas. In a second stage, they can be complemented by higher resolution data and other information to study the observed changes and their underlying factors in detail. The usability of the MODIS VCT product for automated change detection was recently demonstrated. It was used for hot-spotting rapid forest changes in and around protected areas at global scale (Mulligan, 2008). However, since MODIS VCT quantifies for each pixel solely the percentage of tree cover (Hansen et al., 2003), its application is more useful in ecosystems where trees are a dominant feature.

The MODIS LC product has the potential to provide a new way to a regular and more comprehensive monitoring of land cover changes in protected areas at global scale. The product is a time series of global land cover classifications at 500 m resolution, which has been produced annually since 2001 (Friedl et al., 2002, 2010). It distinguishes between 17 land cover classes following the International Geosphere–Biosphere Programme (IGBP) classification scheme (Loveland and Belward, 1997). The comparison of successive years could allow the detection of land cover changes among those classes, expanding the results that can be obtained through the MODIS VCT product. The post-classification comparison is methodologically an easy approach to quantify changes and has been widely used at local and regional studies (e.g., Dimyati et al., 1996; Massart et al., 1995; Wilcock and Cooper, 1993). Its application at continental and global scales has been hampered by the availability of temporally, spatially and thematically consistent input classifications (Lambin and Geist, 2006; Verbont et al., 2011). The MODIS LC time series avoids many of these limitations (for example, thematic differences, spatial inconsistencies or scaling bias), because the product is created using the same sensor and updated using the same algorithm and training dataset. Nevertheless, the post-classification comparison can be prone to classification errors of the input classifications, which accumulate in temporal comparison. The accuracy of the change detection map approximates only the product of the accuracies of the input maps (Stow et al., 1980). A careful testing of the MODIS LC classification is therefore needed.

The objective of this paper is to assess the use of the MODIS LC product for the repeated and automated monitoring of land cover changes at continental scale using the protected areas of Africa as case study. We use the continent-wide classification confidence and change frequency of the MODIS LC time series to identify areas where land cover change can be detected with high, medium or low confidence. We then use this information to assess the proportion and extent of African protected areas where land cover change can be detected, and the degree of confidence of the detection in different ecoregions.

2. Methods

2.1. MODIS land cover type product

Since 2001, the MODIS Land Cover Group at the Boston University has been producing the MODIS land cover type product (MODIS LC, 5th collection). It is the first operational product, which provides annual updates of spatially-explicit global land cover information at 500 m resolution (Friedl et al., 2002, 2010). The main classification scheme of the product follows the legend developed by the International Geosphere–Biosphere Programme (IGBP). It identifies eleven natural vegetation classes, three human developed and three non-vegetated land classes (Belward, 1996). We reduced the number of classes from 17 to 12 (Table 1), excluding the evergreen needleleaf, deciduous needleleaf, mixed forest, snow/ice, and water classes. The three eliminated forest classes correspond in the MODIS LC map to areas of boreal and temperate forest types, which are with less than 0.05% coverage restricted to small mountain tops and thus sparsely distributed in the African continent. The snow/ice and water classes were excluded because of the focus of the study on land cover changes.

<table>
<thead>
<tr>
<th>Code</th>
<th>MODIS LC class</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>EF</td>
<td>Evergreen broadleaf forest</td>
<td>Broadleaf woody vegetation cover &gt; 60%, height &gt; 2 m, canopy is never without green foliage</td>
</tr>
<tr>
<td>DF</td>
<td>Deciduous broadleaf forest</td>
<td>Broadleaf woody vegetation cover &gt; 60%, height &gt; 2 m, annual cycle of leaf-on and leaf-off periods</td>
</tr>
<tr>
<td>WS</td>
<td>Woody savannas</td>
<td>Woody vegetation cover 30–60%, height &gt; 2 m, herbal and other understory cover</td>
</tr>
<tr>
<td>S</td>
<td>Savannas</td>
<td>Woody vegetation cover 10–30%, height &gt; 2 m, herbal and other understory cover</td>
</tr>
<tr>
<td>CS</td>
<td>Closed shrublands</td>
<td>Woody vegetation cover &gt; 60%, height &lt; 2 m, evergreen or decidous</td>
</tr>
<tr>
<td>OS</td>
<td>Open shrublands</td>
<td>Woody vegetation cover 10–60%, height &lt; 2 m, evergreen or decidous</td>
</tr>
<tr>
<td>G</td>
<td>Grasslands</td>
<td>Herbaceous cover, woody vegetation cover&lt;10%</td>
</tr>
<tr>
<td>PW</td>
<td>Permanent wetlands</td>
<td>Permanent mixture of water and herbal or woody vegetation</td>
</tr>
<tr>
<td>C</td>
<td>Croplands</td>
<td>Temporary crops followed by harvest and a bare soil period; perennial crops are classified as the appropriate forest or shrub LC type</td>
</tr>
<tr>
<td>CM</td>
<td>Cropland/natural vegetation mosaic</td>
<td>Mosaic of croplands, forests, shrublands and grasslands in which no one component comprises &gt;60%</td>
</tr>
<tr>
<td>U</td>
<td>Urban and built-up</td>
<td>Buildings and other man-made structures</td>
</tr>
<tr>
<td>B</td>
<td>Barren or sparsely vegetated</td>
<td>Exposed soil, sand, rocks or snow; vegetated cover &lt; 10%</td>
</tr>
</tbody>
</table>

For the present study, the MODIS LC time series was available for the years 2001 to 2009. A pre-analysis of classification consistency between the years, however, showed that the classifier significantly increased or reduced the number of pixels assigned to some classes during the first three years (not shown). The effect disappears from 2003 onwards. We therefore used only years 2003 to 2009 in our analysis.

2.2. African protected areas

We used four management categories of protected areas, with an extent larger than 500 ha, to test the impact of MODIS LC mean classification confidence. The management categories were defined by the International Union for Conservation of Nature (IUCN), providing a framework for the different management approaches and conservation objectives (Dudley, 2008). The four selected categories describe (1) nature reserves plus wilderness areas, (2) national parks, (3) national monuments or features, and (4) habitat/species management areas. Protected areas are catalogued in the World Database on Protected Areas (WDPA), which delineates the boundaries of each site and stores information, including name, type and date of designation, and documented area. The threshold of 500 ha corresponds to circa 23 pixels and ensures that a minimum number of pixels are included in the analysis for each protected area. In total, 652 protected areas were selected from the 2010 WDPA database, representing ca. 45% of the area under formal designation in Africa.

2.3. Mean classification confidence

We calculated a mean classification confidence layer to identify the systematic confidence of classes and regions between 2003 and 2009. The calculation is based on averaging the annual classification confidence layers, which accompany each MODIS LC product. These layers quantify for each pixel the probability that the correct land cover label has been assigned (McIver and Friedl, 2001). It complements the classical metrics of accuracy assessment for the overall product and individual classes, and allows each year to identify classes and regions, for which MODIS LC has obtained more reliable classification results. Averaging the annual values gives an indication of the overall classification confidence for the whole MODIS LC time series.
Beyond that, the analysis of classification confidence provides information on the reliability of the land cover change estimates. We based our analysis on the square of the mean classification confidence layer. The result indicates the probability that the correct land cover change can be detected during this period. This calculation incorporates the idea that the accuracy of change detected between individual classifications approximates the multiplication of the input classification accuracies (Stow et al., 1980). It means, for example, that a change confidence of 36% can be expected for a pixel that is systematically classified with 60% mean classification confidence.

To test the impact of mean classification confidence on the monitoring of land cover changes in protected areas, we selected three thresholds that comply with commonly achieved classification accuracies. The thresholds were: 60%, 80% and 90% mean classification confidence, corresponding to an average of 36%, 64% and 81% change confidence. For each threshold we flagged those protected areas, where at least 60% of pixels satisfy the threshold. The results were summarised by ecoregion (White, 1983). Sites falling into more than one ecoregion were counted for each.

2.4. Temporal consistency

For each pixel, we also counted the change frequency to assess the temporal consistency of the MODIS classifier against the inter-annual variability of land cover. The layer gives for each pixel the number of times it has changed its land cover label between 2003 and 2009. We assume that higher change frequencies are more likely caused by the sensitivity of the classifier to inter-annual biomass variations than by a real land cover change.

3. Results

3.1. Mean classification confidence

The analysis of mean classification confidence showed that 30% of the African continent is systematically mapped with classification confidences above 90%. These areas lie almost exclusively in the Sahara (75%) and Guineo-Congolian (16%) ecoregions (Fig. 1a). Land cover classes with the highest mean classification confidence are the barren/sparsely vegetated (B) and evergreen broadleaf forest (EF), where respectively 75% and 59% of pixels have been systematically classified with more than 90% confidence (Fig. 1b). Other areas mapped with high confidence are found in homogeneous land cover terrains, such as the woody savannas in Central Africa, the coastal deserts in Namibia and the rainforests in Madagascar (Fig. 1a).

The mean classification confidence decreases rapidly in transitional and heterogeneous terrains, such as the ecoregions of the Sahel-Sudanian belt, the East African Rift in Ethiopia, and the eastern and coastal areas of South Africa (Fig. 1a). These terrains are characterised by a mix of savannas (WS, S), shrubs (CS, OS), grasslands (G) and croplands (C, CM). The percentage of these vegetation classes systematically classified with confidence above 90% is maximally 2% (Fig. 1b). Between 53% and 82% of pixels allocated to these vegetation classes are mapped with mean classification confidence lower than 70%. The confidence decreases also along large river systems and mountain ranges of the Saharan and Guineo-Congolian ecoregions.

3.2. Temporal consistency

Between 2003 and 2009, the MODIS LC classifier assigned 69% of the pixels always to the same land cover type (Fig. 2a). The remaining pixels (about one third) were allocated over time to two, three or more land cover types.

The barren/sparsely vegetated (B), evergreen broadleaf forests (EF) and urban (U) classes were the most consistently classified land cover types (Fig. 2b); with about 90% of pixels always assigned to the same land cover label. Nevertheless, about 8% of pixels classified as evergreen broadleaf forest and urban in 2003 changed land cover type at least twice by 2009.

The frequency of change in land cover classification is highest in heterogeneous landscapes and at the edges of homogeneous land cover areas. Pixels with higher frequencies of change were concentrated in areas like the Sudanian ecoregion, the Great Rift Valley, the lower reach of the Congo River and the east of South Africa (Fig. 2a). These

Fig. 1. Distribution (a) and frequency (b) of mean classification confidence values for MODIS LC, calculated from 6 consecutive years of the MODIS LC product (2003–2009). The higher the values the more systematically regions (a) and classes (b) have been classified with high classification confidence over this period. The square of the mean classification confidence is indicative for the likelihood that the correct land cover change can be detected in a region (a).
regions were mainly characterised by a mix of deciduous broadleaf forests, savannas, shrublands, grasslands, wetlands and human developed land.

Additionally, pixels classified by (semi) open natural vegetation types (WS, S, OS, G, PW) in 2003 tended to have been less frequently reclassified by 2009 than arable land types (C, CM) (Fig. 2b). Instead, deciduous broadleaf forest (DF) and closed shrublands (CS) were the classes with the highest frequencies of change. The frequent changes of pixels classified as deciduous broadleaf forest (DF) stands in sharp contrast to the more consistently classified evergreen broadleaf forest (EF) class.

3.3. Monitoring protected areas

With increasing mean classification confidence, the number and extent of protected areas that can be monitored by MODIS LC decreases (Table 2). Land cover was mapped with less than 60% mean classification confidence (corresponding to less than 36% change confidence) in 351 out of 652 protected areas, covering 20% of the total area protected in Africa. More than 80% of these protected areas are in the Cape, Kalahari-Highveld, Somali-Masai, Tongaland-Pondoland, Afromontane and West-Malagasy ecoregions. Overall, in 98% of the protected territory in Tongaland-Pondoland, 97% in Cape and 89% in

<table>
<thead>
<tr>
<th>Ecoregion</th>
<th>Total # PA</th>
<th>extent (1000 km²)</th>
<th>MCC&gt;60% # PA</th>
<th>% extent</th>
<th>MCC&gt;80% # PA</th>
<th>% extent</th>
<th>MCC&gt;90% # PA</th>
<th>% extent</th>
</tr>
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<tr>
<td>Mediterranean</td>
<td>5</td>
<td>0.5</td>
<td>2</td>
<td>27</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mediterranean/Sahara</td>
<td>2</td>
<td>0.7</td>
<td>2</td>
<td>100</td>
<td>6</td>
<td>91</td>
<td>4</td>
<td>88</td>
</tr>
<tr>
<td>Sahara</td>
<td>9</td>
<td>200.4</td>
<td>7</td>
<td>100</td>
<td>6</td>
<td>91</td>
<td>4</td>
<td>88</td>
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<tr>
<td>Sahel</td>
<td>15</td>
<td>141.5</td>
<td>12</td>
<td>98</td>
<td>3</td>
<td>19</td>
<td>3</td>
<td>19</td>
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<tr>
<td>Sudanian</td>
<td>81</td>
<td>224.6</td>
<td>37</td>
<td>60</td>
<td>3</td>
<td>3</td>
<td></td>
<td></td>
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<tr>
<td>Guinea-Congolia/Sudania</td>
<td>28</td>
<td>38.4</td>
<td>21</td>
<td>89</td>
<td></td>
<td></td>
<td></td>
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<tr>
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<td>55</td>
<td>147.5</td>
<td>53</td>
<td>97</td>
<td>33</td>
<td>86</td>
<td>20</td>
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<tr>
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<td>3</td>
<td>6.3</td>
<td>2</td>
<td>11</td>
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<td></td>
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<tr>
<td>Lake Victoria</td>
<td>21</td>
<td>18.7</td>
<td>11</td>
<td>57</td>
<td>3</td>
<td>5</td>
<td>1</td>
<td>4</td>
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<tr>
<td>Afromontane</td>
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<td>27.7</td>
<td>31</td>
<td>39</td>
<td>4</td>
<td>4</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Somalia-Masai</td>
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<td>102.7</td>
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<td>28</td>
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<td>Zanzibar-Inhambane</td>
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<td>20.0</td>
<td>15</td>
<td>87</td>
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<tr>
<td>Zambeian</td>
<td>154</td>
<td>358.3</td>
<td>79</td>
<td>81</td>
<td>1</td>
<td>&lt;1</td>
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<tr>
<td>Kalahari-Highveld</td>
<td>48</td>
<td>100.3</td>
<td>6</td>
<td>90</td>
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<tr>
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<td>97.9</td>
<td>16</td>
<td>98</td>
<td>1</td>
<td>1</td>
<td></td>
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<tr>
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<td>35</td>
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<td>1</td>
<td>3</td>
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<tr>
<td>Tongaland-Pondoland</td>
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<td>7.0</td>
<td>9</td>
<td>2</td>
<td></td>
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<td></td>
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<td>West Malagasy</td>
<td>21</td>
<td>6.6</td>
<td>7</td>
<td>18</td>
<td>2</td>
<td>4</td>
<td>1</td>
<td>&lt;1</td>
</tr>
<tr>
<td>East Malagasy</td>
<td>23</td>
<td>7.2</td>
<td>17</td>
<td>87</td>
<td>15</td>
<td>81</td>
<td>13</td>
<td>80</td>
</tr>
<tr>
<td>Africa</td>
<td>652</td>
<td>1510.0</td>
<td>301</td>
<td>80</td>
<td>69</td>
<td>23</td>
<td>40</td>
<td>21</td>
</tr>
</tbody>
</table>

* The sum of PAs observed per ecosystem is higher than the total number of PAs observed for Africa, because some PAs cover more than one ecosystem type.
Guinea-Congolian/Zambezia, land cover changes can be monitored with less than 36% change confidence.

At mean classification confidence above 80% and 90% (corresponding to 64% and 81% change confidence), land cover changes are detectable in only 69 and 40 protected areas, respectively (Table 2). They correspond to less than 23% of the protected territory. These areas are primarily located in the Sahara, Guinea-Congolian and East Malagasy ecoregions (Table 2). Even though, 75% of the protected territory in the Mediterranean/Sahara ecoregion is classified with at least 80% mean classification confidence, it corresponds to only one protected area.

4. Discussion

4.1. Methodological accuracy and ecological dynamics

The MODIS LC classifier achieves the highest classification confidences in ample landscapes homogeneously covered by either bare soils (e.g., Saharan and Namib Desert) or by evergreen broadleaf forests (e.g., rainforests of Central Africa, West Africa and Madagascar). Both land cover classes have significant spectral signals on satellite images and can therefore generally be well mapped with high classification accuracies (Herold et al., 2008). Human activities, however, concentrate along the Nile and Congo rivers and along the forest edges, where the confidence of the change assessment decreases.

Classification uncertainties and change frequencies increase significantly in heterogeneous landscapes and transition zones between major land cover types. Savannas, shrublands, grasslands and croplands are particularly difficult to be separated by remote sensing techniques (Mauxaux et al., 2004). Land cover types grade into each other making their discrimination into sharply defined land cover classes prone to confusions. In West Africa, for example, slash-and-burn agriculture is hardly distinguishable from natural savannas because they grade into each other both spatially and temporally. Also, high fire frequency in savannas (Groen et al., 2008; Klop and Prins. 2008; van Langenvelde et al., 2003) may contribute to their classification as grasslands or croplands.

The temporal inconsistency of the MODIS LC product may be caused by the classifier’s sensitivity to plant biomass variations. The algorithm is partly based on the interpretation of the enhanced vegetation index (Strahler et al., 1999), which causes the classifier to separate classes depending on the available amount of biomass. Particularly in drier ecosystems, however, inter-annual rainfall fluctuations have a major effect on plant biomass production and tree cover growth (Coe et al., 1976; Drent and Prins, 1987; Holmgren et al., 2001, 2006). In successive years, an area can therefore be interpreted by the classifier into different classes because of this variation even though its vegetation structure and floristic composition remained unchanged.

For savannas, shrublands, grasslands and croplands it is particularly challenging to evaluate whether a change in the MODIS LC product is due to inter-annual class confusion or to a real land cover change. Some of the transitions between these vegetation states can occur rapidly depending on climate conditions and disturbance regimes (Acacio et al., 2009; Holmgren and Scheffer, 2001; Sitters et al., 2012; Trodd and Dougill, 1998; van de Wouw and et al., 2011). The combination of methodological challenges and ecological dynamism in these systems can introduce errors in an automatic land cover change detection process. The aggregation of (1) savannas, shrublands and grasslands in one vegetation category and (2) croplands and cropland mosaics in a second one, can partially address this problem. But it obviously reduces the level of thematic resolution at which vegetation changes can be described. Moreover, distinction between these natural open vegetation types and cultivated land remains challenging (Mauxaux et al., 2004). While the observation of land cover changes between natural and cultivated land are more relevant from a conservation perspective, their observation from MODIS LC remains uncertain.

Our analysis showed that urban areas have low change frequencies. Nevertheless, about 4% of pixels classified as urban in 2003 changed their land cover type once till 2009 and another 9% changed at least twice. It can be assumed to be unlikely that an area once turned into urban will change into another land cover type in such a short period. Two changes can be considered to be even more unlikely.

A more detailed analysis of this change showed further that the automatic classifier only allows pixels that were classified as urban areas to change into wetlands (not shown). These allotment swaps are questionable, even more since they occur even distantly from ‘true’ wetlands or other water bodies, and might be due to the processing of the input data.

4.2. Automated monitoring of land cover changes in protected areas

The certainties and uncertainties of the MODIS LC time series have implications on its ability to monitor land cover changes in protected areas. High certainty about the nature of the changes detected is most likely to be found in protected areas covered by extensive stands of evergreen broadleaf forest (EF) or bare arid lands (B). These sites are mainly located in the Guinea-Congolian, East Malagasy and Sahara ecoregions. About 70% to 90% of their extent of core protected areas can be regularly monitored by MODIS LC, with change confidences of 81% and above. However, most of these parks are remote from human populations and therefore naturally protected from direct human disturbances. Exceptions are the parks in East Malagasy and a few sites in the Guinea-Congolian ecoregion, with intensive land use next to the park boundaries. MODIS LC could in this context play a role in automatic warning system based on land cover change detection, allowing for targeted quantitative land cover change studies, although ground-truthing is still advised.

Most parks, however, lie in heterogeneous and transitional landscapes. MODIS LC classification uncertainties and change frequencies increase distinctly in these areas. In almost 90% of African core protected areas (about 77% of their extent) land cover changes can be mapped only up to 64% confidence while especially in many small sites, the detected land cover changes reach a maximum of 36% confidence. These protected areas lie in savannas and afromontane habitats, often in the vicinity of human populations. These sites are more exposed to direct human disturbances impacting the land cover, such as subsistence and commercial agriculture, livestock farming, wood cutting and fire use for poaching. The regular monitoring of land cover changes in these areas is crucial for the timely detection of conservation conflicts. A change confidence of 36 to 64% is however too low to be used as basis for the planning and implementation of conservation programmes.

5. Future directions

Our analysis showed that automatic monitoring of land cover changes with MODIS LC in Africa has considerable limitations in detecting land cover changes in key habitat types like croplands, grasslands, savannas, shrublands, and mountain areas as well as in heterogeneous regions more closely affected by human disturbances. The method is therefore currently unsuitable for an automatic monitoring of land cover changes in protected areas at continental scale.

Other approaches could contribute to automate the change detection process over vast areas. For instance, the change vector analysis (Malila, 1980) of annual MODIS reflectance mosaics might offer such an opportunity. Rather than comparing two land cover classifications, the method builds on the calculation of a spectral vector between two reflectance images. The change vector describes the magnitude and direction of the change. However, the method makes it difficult to:

1. define a minimum threshold of change magnitude to distinguish change from no-change and
2. interpret the change direction (i.e. to label the from-to-change). The web-based land cover tool
presented by Bastin et al. (2012) might facilitate this process. Furthermore, the calibration of the change image with annual rainfall time series will be crucial to account for inter-annual biomass variations due to rainfall fluctuations.

At a time where representative networks of efficiently managed protected areas are being developed and established, an accurate assessment of the threats affecting these areas, in particular the land cover change, is more necessary than ever. Technicians and scientists are thus being required to produce reliable and replicable results for authorities to support the early detection of conservation conflicts and the efficient direction of human and financial resources. In these conditions, we conclude that the analysis of series of yearly MODIS LC demonstrates a limited utility for quantitative measurements, but could be used as detection tool in stable ecoregions.

References


