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Rapid mapping and impact estimation of illegal charcoal production in southern Somalia based on WorldView-1 imagery

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ABSTRACT

Following more than 20 years of civil unrest, environmental information for southern Somalia is scarce. Wood charcoal production and export is a major activity supporting war regimes in this area such as the extreme Islamist group Al-Shabaab. However, little quantitative information exists on the extent of this charcoal production. In this study, we developed a semi-automatic detection method to identify charcoal production sites from very high resolution (0.5 m) satellite imagery. We then applied it to a 4700 km^2 area along the Juba River in southern Somalia using 2011 and 2013 WorldView-1 imagery. Based on the sites detected exclusively for 2013 we estimated an average production of 24,000 tonnes of charcoal and 2.7% tree loss for the two-year interval, using literature- and local-knowledge-based assumptions on likely ranges of kiln and tree parameters. Our large-area assessment helps to better understand the dimension and impact of charcoal production in southern Somalia and reveals a rapid depletion of tree cover. The analysis provides a first step towards the development of a charcoal production monitoring system that could be extended to other parts of the country.

Introduction

In developing countries woodfuel accounts for 67 to 80% of the total energy used (FAO, 2010) and is the main source of household energy (Zulu and Richardson, 2013). The woodfuel related market is an important source of income for many people (Clancy, 2008). Evidence exists that at the local level it can have significant impacts on forest degradation (FAO, 2010; Kanninen et al., 2007). Woodfuel refers to any energy source that is derived from woody biomass. These include fuelwood, charcoal, wood pellets, biogas, cellulosic ethanol, and other forms of bioenergy. Charcoal is the dominant form of woodfuel used by urban households in Africa and other developing countries (Akpalu et al, 2011).

Charcoal is a woodfuel made by burning wood in a low-oxygen environment. Compared to wood, it weighs about five times less and produces more heat per kilogram (Boucher et al., 2011) making it a more efficient form of transporting woodfuel (Akpalu et al, 2011). According to FAO statistics, Africa produces 60% of the global charcoal production (FAO, 2014). However, these charcoal production estimates are often inaccurate when disaggregated at the national level. For many African countries, detailed information is lacking partly due to the informality and clandestine nature of production sector and the scattered production by rural population (Mwampamba et al, 2013). Estimates are consequently based on analytical and projection models that use woodfuel information of countries in similar socioeconomic and geographical situations, or by multiplying the country population by a per capita estimate based on a literature review carried out in 1980 (Wardle and Pontecorvo, 1981; Whiteman et al., 2002). The datedness of some of the estimates that are used as input in combination with the difficulty of data collection, makes that national charcoal production data are often at best "guesstimates" with limited accuracy (Mwampamba et al., 2013). Levels of woodfuel harvesting may be in balance with the productive capacity of the wood stocks, but overall tree loss occurs when the intensity of woodfuel production prevents regeneration and therefore sustainable production (Ribot, 1998).

In Somalia, charcoal production is not only triggered by domestic consumption, which accounts for only a fifth of the total production and is the main source of energy in urban areas such as Mogadishu and Hargeisa, but mostly by foreign demand, which accounts for the remaining 80% (UNEP, 2005). In fact, charcoal has developed into one of the major export products, and is sometimes referred to as "black gold" (Bakonyi and Abdullani, 2006; UN Security Council, 2011). UNEP (2005) estimated that 4.4 million trees are logged annually to produce the 250,000 tonnes of charcoal that is exported every year from Somalia to Saudi Arabia, Yemen and the United Arab Emirates. While part of the charcoal exported from Somalia may originate from

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neighboring countries like Ethiopia, the bulk of the exported charcoal is produced in Somalia itself (Belward et al., 2011). Even if national production estimates may be inaccurate (Mwampamba et al., 2013), the FAO database indicates a significant increase in production levels, i.e. from about 180,000 tonnes in 1961 to 420,000 tonnes in 1991, to almost 1.2 million tonnes in 2012 (FAO, 2014). Since the collapse of Somalia's central government in 1991, militia groups fight for political control and finance their activities partly with illegal charcoal exports (UN Security Council, 2011; UNEP, 2014). For this reason, in February 2012 under resolution 2036 the UN Security Council banned charcoal export from Somalia, regardless of the origin of the charcoal. The charcoal trade is the main driver of the fast depletion of forests and woodlands in Somalia (UNEP, 2005).

Despite high exports of charcoal from Somalia, and its contribution to tree cover loss, consequent land degradation (Omuto et al, 2009; Richardson et al., 2010), and reduction of ecosystem services provided by trees (ICRAF, 2014), little quantitative information on tree cover loss in Somalia during the past two decades is available. Moreover, Somalia is predicted to be one of the nine African countries that will face water scarcity by 2025 (Boko et al., 2007), and therefore land degradation will worsen the water scarcity effects by increasing the population's vulnerability to drought (Holleman, 2003). Existing studies on tree cover loss have focused on the north-eastern part of Somalia (MPDES-CHE, 2004; Oduori et al., 2009), because in that region fieldwork was possible due to the relatively better security situation. For example, a recent study by FAO investigated tree loss of an area located in the arid Sool-Sanag Plateau, in northern Somalia, characterized by sparse vegetation (Oduori et al., 2011). The researchers estimated a tree loss of about 13% between 2001 and 2006, based on visually identified individual trees from aerial photos covering eight sampling frames, for a total area of 128 km^2. The only recent study available for southern Somalia estimated a tree loss of 7.2% over the period 2006–2012 for two sample areas covering about 60 km^2 in southern Somalia (Rembold et al., 2013).

Given the limited security in large parts of Somalia in the last 20 years, and especially in the southern and central parts of the country since 2006, when the Islamist terrorist group Al-Shabaab took control, field surveys have been impossible to execute and consequently direct evidence of tree cover changes can exclusively be obtained through remote sensing. Using medium resolution MODIS imagery (500 m), Miles et al. (2006) assessed the distribution of tropical dry-forest at the global scale, while Brink et al. (2014) monitored 20 years of land cover change in Eastern Africa with 30 m resolution Landsat data. However, for charcoal production in Somalia, tree cover clearances typically occur in a patchy distribution (Oduori et al., 2011) that may not be detected, or at least not accurately, following change detection with MODIS-type imagery (Ryan et al., 2012) or on a widely spaced grid of Landsat imagery (Brink et al., 2014).

DeFries et al. (2007) suggested that for monitoring small-scale changes in forest cover the use of aerial photos or high resolution (10–60 m) satellite imagery is appropriate. Studies in the low density forests and tiger bush areas of northern Somalia indicate that accurate estimation of tree-cutting rates requires the detection of changes in the presence of individual trees (Oduori et al., 2009; Oroda et al., 2007). However, in southern Somalia where charcoal production typically occurs in the denser parts of dry woodlands or woody savannah it can be hard to discern individual trees, even from very high resolution imagery. In fact, about 50% of southern Somalia is covered by such areas, comprising the *Acacia–Commiphora* deciduous bushland and thicket ecoregion (White, 1983). Rembold et al. (2013) showed that for those areas loss of tree cover can be estimated by the identification of charcoal production sites, as they form clear circular objects that are spectrally different from their surroundings. In general for efficiently detecting single objects from remotely sensed data, the spatial resolution of the images should be less than half the object size (Woodcock and Strahler, 1987). Hence, to detect small charcoal production sites in Somalia (approximately 3–10 m in diameter), only aerial photos and very high resolution (<5 m) satellite imagery provide the required resolution. Rembold et al. (2013) used visual interpretation of very high resolution imagery to identify changes in charcoal production sites for a relatively small area of 60 km^2. However, for larger areas visual interpretation requires large time investments, so rapid (semi-) automated techniques are required that can reduce interpretation costs. The objective of this study is to assess regional (>4000 km^2) tree cover loss in southern Somalia due to charcoal production using semi-automated identification and mapping of charcoal production sites from very high resolution (VHR) satellite imagery.

Study area and data

For this study we selected a study area in the south-western part of Somalia that was known to be a key production zone (Rembold et al, 2013) and for which multi-temporal WorldView-1 imagery was available (Fig. 1). WorldView-1 imagery covered nearly 6000 km^2 for February and March 2011 (16 scenes of 18 February and 8 scenes of 3 March) and for February 2013 (16 scenes of 19 February and 11 scenes of 23 February). The WorldView-1 sensor produces panchromatic images with a resolution of 0.5 m. All images were acquired during the main dry season (locally known as *Jiilaal*) of the respective year which covers February and March. The satellite sensor therefore recorded the land cover in similar climatic conditions. For our analysis the digital numbers contained in the imagery were converted to top-of-atmosphere reflectance using standard radiometric calibration procedures (Chander and Markham, 2003), taking WorldView-1 specific calibration coefficients and parameters delivered with each image as input. This is a standard procedure that corrects the digital numbers contained in scenes of different acquisition dates for the effect of relative sun illumination and satellite viewing angles.

The study area boundaries were defined by considering the area covered by 2013 imagery that was also available for 2011. From the imagery available, large contiguous areas of agricultural land were digitized by visual interpretation (based on presence of structures like neat field contours, fences, roads, and villages). These areas can be easily and quickly identified, and were excluded from the research analysis, since charcoal production only occurs where natural woody vegetation is found. Hence, the final area of interest used for this research comprised a dry woodland area of approximately 4700 km^2 that extends on both sides along the Juba River, and is geographically located between the city of Bu'aale in the north and the port city of Kismayo in the south (Fig. 1).

Access to the area has been limited since the beginning of the civil conflict in the early 1990s, and impossible from 2006 to date under the control of Al-Shabaab. After the capture of Kismayo port by Kenyan forces in September 2012, conflicts over political power arose between local groups that declared autonomy for sub-regions and the federal government in Mogadishu. Despite a new agreement for the establishment of the Interim South West Administration comprising the regions of Bay, Bakool and Lower Shabelle (UN News Centre, 2014), it is unlikely that in the near future south-central Somalia will have a stable well-functioning government, much needed to effectively oppose to Al-Shabaab's influence (International Crisis Group, 2014).

The most common charcoal production method in the study area is known as the Bay Method, and it was described by Robinson (1988). To produce charcoal, a type of oven known as 'kiln' is used. Kilns are built by piling the timber straight on the soil floor. The timber is collected from the surroundings and arranged into a circular mound with stronger poles erected at the center, and other shorter pieces of wood positioned around it. The mound is packed as close as possible, and the gaps are filled with smaller pieces of wood, shrubs, and grass to facilitate kiln lighting. The whole structure is then covered with iron sheets and finally buried with sand and loose soil. The study conducted by Robinson (1988) revealed a carbonization time ranging from 3 to

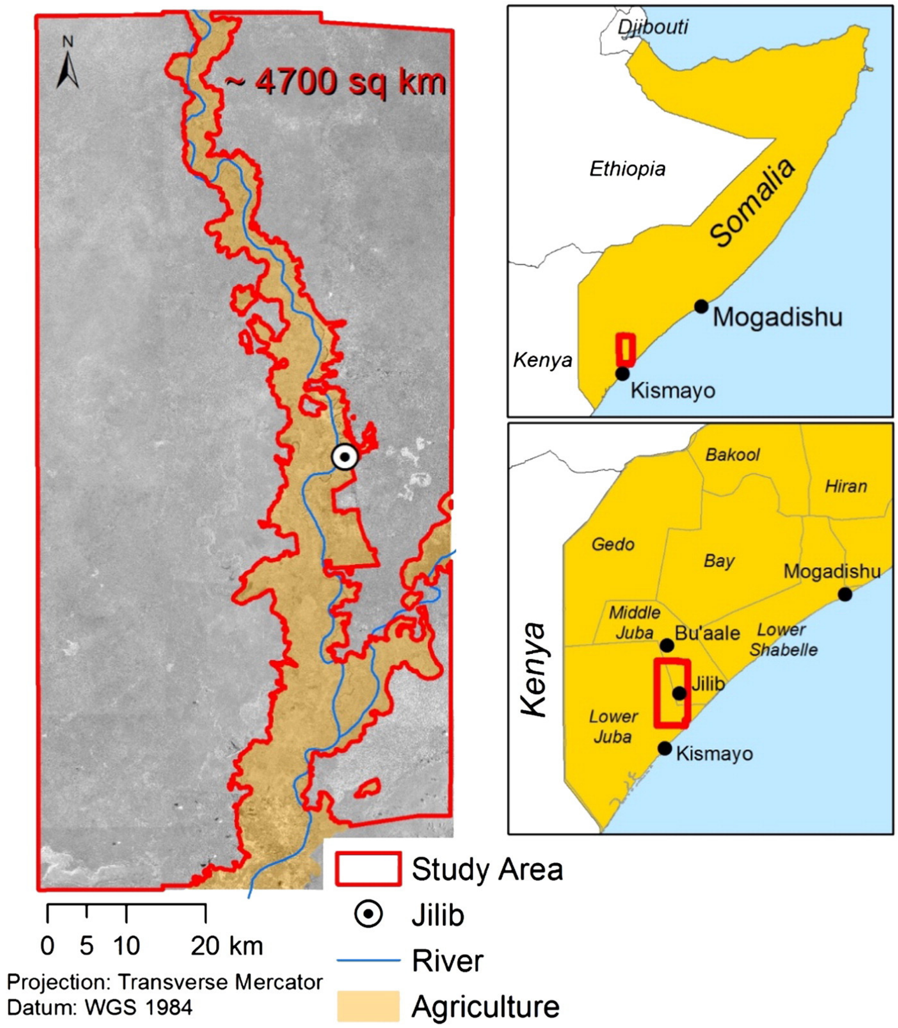

Fig. 1. Study area on the east and west of the Juba River. A central strip of agricultural land was digitized by visual interpretation and excluded from the analysis as charcoal production only occurs where dry woodland is found.

8 days, and cooling time between 9 and 12 days, depending on timber's quality, quantity, and moisture content. Once the burning process is completed, the kiln is uncovered, the charcoal is taken out with care not to further fragment single pieces and it is filled into bags. FAO experts confirmed that an individual kiln is used only once and that charcoal production mostly takes place during the dry season. The study conducted by Robinson (1988) indicates that the timber necessary to build a kiln was traditionally collected by donkey and cart and taken to a central site, near the site where the timber was felled, and the furthest distance covered in the case of the evaluation trials was 200 m. Once the charcoal is collected, the layer of black ashes and charcoal residues left on the ground is clearly visible as a round dark spot on very high resolution imagery, such as WorldView-1. We hypothesize that the recent charcoal production process in southern Somalia is carried out with a more industrial process with larger kilns, high numbers of workers and using trucks for transport.

Methods

Detection of charcoal production sites

We used object-based image analysis to identify charcoal production sites on WorldView-1 imagery. Using the software eCognition (Baatz and Schaepe, 2000; eCognition, 2013) we constructed a set of rules taking into account the specific spatial and spectral features of the charcoal production sites. Typically, charcoal production sites appear as isolated dark spots with an approximate shape of a circle against a lighter soil background. The first step of the rule set was to group image pixels into spatial segments at a scale appropriate for charcoal sites. Second, darker segments of a specific reflectance range were selected as potential charcoal production sites. This reflectance based rule excludes other circular elements of similar shape and size, but with different spectral properties (e.g. ant or termite colonies). Finally, from these potential sites we selected circular segments within a range of 3 to 9 m radius (comparable with the size of charcoal sites). The lower limit of 3 m allowed to exclude many small tree shadows, while visual interpretation showed that sites with a radius larger than 9 m radius did not occur and if detected, rather related to fire occurrence. A more detailed description of the methodology implemented in eCognition is added as supplementary material to this paper.

The different elevation and azimuth angles, together with different dates of image acquisition and relative atmospheric conditions, influence the reflectance values of the images (for example by recording larger tree shadows). The reflectance threshold values of the rule set were kept identical among images with the same date, while different values were tested and applied to different dates (Table 1). Different reflectance threshold values reflect differences in image characteristics due to the particular elevation and azimuth angles of Sun and satellite at the time of image acquisition. Other rule settings were not adapted

Table 1
Threshold values used for the rule set. Only reflectance threshold values were adapted to image characteristics with the aim to detect as many actual sites in the pilot area as possible. Roundness and asymmetry are the two eCognition software functions used in combination to select segments with an approximate circular shape.

Date	Reflectance	Roundness	Asymmetry	Radius size (m)
18-Feb-11	≤0.122	≤0.45	≤0.4	≥3 ≤ 9
03-Mar-11	≤0.138	≤0.45	≤0.4	≥3 ≤ 9
19-Feb-13	≤0.134	≤0.45	≤0.4	≥3 ≤ 9
23-Feb-13	≤0.099	≤0.45	≤0.4	≥3 ≤ 9

for the different dates. The rule set was first developed on four 1 × 1 km pilot areas for rapid computation and the same areas were also visually interpreted to assess performance. The threshold values applied in the rule set were selected in a trial-and-error procedure whereby we aimed to merely detect actual sites in the pilot areas, while simultaneously detecting as many sites as possible. The training (or reference) set for each area consisted of visually-identified production sites. Following the effective tuning of the rule set to accurately detect charcoal production sites for the training set, the rule set was applied to the entire study area for both the 2011 and 2013 coverage.

Accuracy assessment

Accuracy assessment is ideally performed using field reference data. Due to the security situation in southern Somalia field data collection was not feasible. Instead we acquired reference data by visually interpreting the imagery in 1 × 1 km sample blocks. A two-stage cluster sampling was implemented by building a grid of 1 × 1 km across the study area (Köhl et al., 2006). In the first stage, a random sample of clusters was selected to cover 10% of the total dry woodland area. In the second stage, all charcoal production sites within the selected clusters were identified by visual interpretation. A total of 419 clusters were selected and used for the analysis of both dates. The advantage of the two-stage cluster sampling for this study is the reduction of the visual interpretation to just a small random part of the entire coverage, which provides sufficient statistical support to represent the entire image coverage for validation purposes.

Two accuracy measures were calculated: the user's and the producer's accuracy. The user's accuracy provides a measure of the probability that a location labeled as a charcoal production site by the rule set is an actual charcoal production site (as identified from visual interpretation). The producer's accuracy refers to the probability that an actual charcoal production site is classified as such by the object based image analysis.

Change detection

Following the semi-automated detection of charcoal sites for 2011 and 2013 images, numbers and locations of detected production sites were compared between both years. By intersecting identified sites for the two years, sites were separated into three groups:

- Sites detected in both years, representing old (2011) sites that are still visible in 2013;
- Sites detected only on the 2011 images, i.e. sites built prior to the 2011 acquisition dates; and no longer visible on the 2013 image (i.e. sites where dark ashes were fully or partially decomposed in the soil, washed away by rain, covered by new soil material transported by winds, or new vegetation emerged);
- Sites detected only on the 2013 images, i.e. sites built prior to the 2013 acquisition dates, but after 2011.

Wood volume and tree loss assessment

The amount of charcoal produced within the study area, and the related wood burnt, can be estimated by linking the identified number and size of charcoal production sites with the production capacity of each site. To estimate the volume of timber used, we assumed the kiln mound to be comparable to a spherical cap. The list below identifies the relevant parameters for the calculations and their ranges. These ranges were derived from existing studies and local expertise.

– To calculate the volume of the spherical cap, two values are needed: the height of the spherical cap, and the radius of the base circle. Based on local expertise and previous studies (MPDES-CHE, 2004), we assumed two possible kiln height values, i.e. 1.5 m and 2.0 m. Since the implemented rule set only identifies objects with an approximately circular shape as charcoal production sites, the kiln radius of each site was derived from its corresponding segment area (dividing by π and taking the square root). We subtract one meter from that radius to account for some spreading out of the charcoal after the kiln is uncovered and the charcoal is transferred into bags.
– The timber stacking inevitably leaves gaps between timber pieces and other materials that are used for the kiln construction (grasses and shrubs for kiln lightning). Therefore, we assumed a range between 20% and 40% of volume subtraction to account for space occupied by air and other materials.
– We assumed a wood-to-charcoal conversion efficiency of 20% based on values provided by the majority of sources for this type of charcoal production in Somalia and other tropical regions (Bird and Shepherd, 1989; ICRAF, 2014; MPDES-CHE, 2004; Robinson, 1988). Nonetheless we acknowledge that current more 'industrial' charcoal production practices may have reduced efficiency levels as compared to cited studies, but hard data on this are lacking.
– Water is present in wood, both in bound form in cell walls, and as free water inside cells and between cell cavities. We set the average timber moisture to 47% following Bird and Shepherd (1989) and Robinson (1988).
– The dry-wood density is the wood mass per unit of volume and it differs for different tree species. We assumed this density to range between 500 kg/m^3 and 700 kg/m^3 based on the key species *Acacia bussei*, *Acacia senegal*, *Acacia tortilis*, and *Terminalia* species (Bird and Shepherd, 1989; Robinson, 1988).

Following Rembold et al. (2013), we estimated the number of trees logged as a function of the number of charcoal production sites and the average number of trees used per kiln. The study suggested an average of two bags of charcoal produced from a single average Acacia tree. We translated charcoal weights into charcoal bags by dividing the weight by 27 kg (i.e. the standard weight of a charcoal bag). The number of bags was then used to calculate the number of trees logged. Finally, the loss of tree cover was related to a tree density of 3400 per km^2, estimated by Rembold et al. (2013) through visual interpretation of ten sites of one hectare on a 2006 Quickbird image (0.65 m) subset of the study area.

Results and discussion

Charcoal detection and validation

Through the semi-automatic analysis of WorldView-1 imagery we could detect most of the actual charcoal production sites occurring within the study area for the two years analyzed. Fig. 2 shows a subset of the study area where the number of charcoal production sites increased between 2011 and 2013. The production sites are clearly visible as darker spots on the two scenes on Figs. 2a and c, while Figs. 2b and d show the corresponding semi-automatically identified sites.

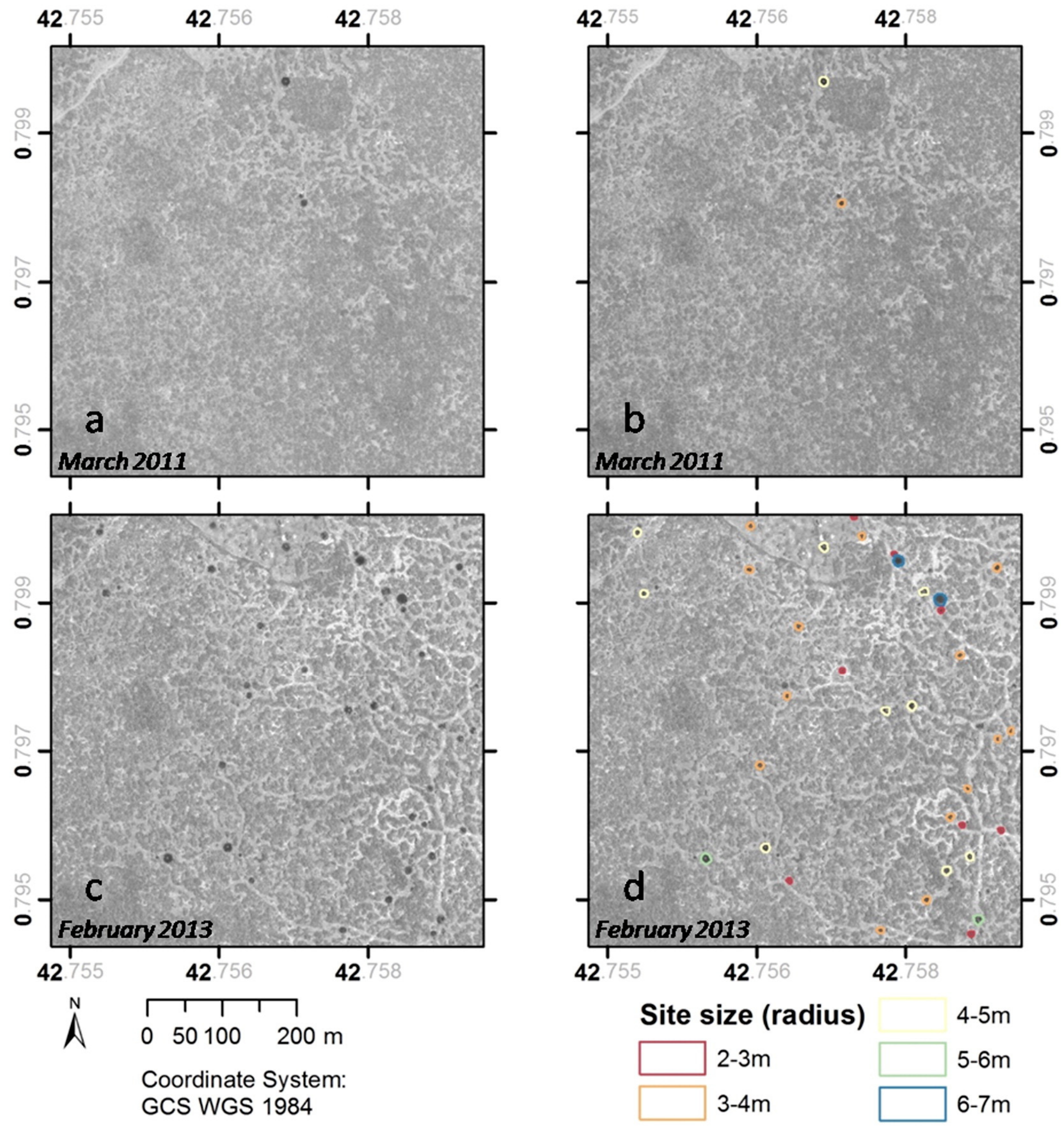

Fig. 2. Illustration of WorldView-1 imagery for 2011 and 2013 and the results of our semi-automatic extraction procedure for an area with charcoal production increase: a) part of the 3 March 2011 WorldView-1 scene; b) the corresponding charcoal production sites detected with the colors indicating the automatically-identified radius of these sites; c) same area imaged by WorldView-1 on 19 February 2013; and d) the corresponding sites detected. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2 shows the accuracy assessment results for the randomly selected sample of 1 × 1 km clusters, separately for each image date. The performance of our rule set is different for each date, with highest user's and producer's accuracy obtained for the dataset of 3 March 2011, and the lowest accuracies for the image of 18 February 2011 that contains larger tree shadows due to the combination of sun and satellite view angle.

We visually examined the classification errors, which can be separated into 1) omission errors, i.e. existing charcoal production sites that were not identified by our method, and 2) commission errors, i.e. non-existing sites erroneously identified by our method as charcoal production sites. Omission errors could be largely attributed to two factors. First, the size threshold: the minimum radius size of 3 m helped excluding many small tree shadows, but at the same time it may have excluded smaller charcoal production sites. Based on our visual examination, these smaller sites make up for less than 5% of all sites and are in most cases found adjacent to larger sites. Local experts indicated that these small kilns are used after the main kiln is uncovered to re-burn wood not completed carbonized in the main kiln. Due to their small size they have a relatively limited contribution to the overall charcoal production (see also Table 6). Second, the semi-automatic approach did not consider sites with irregular shapes. Irregular shapes of charcoal ashes belong to sites of generally older age, because either winds have partially covered the site with soil material, the organic matter (ashes) are decomposed in the soil, charcoal ash are washed away by rain, or new vegetation emerged on the site. Therefore the omission error for recent sites is actually lower. Instead, the commission errors are mainly associated with larger tree shadows or areas burnt in patchy forms, as their shape, size, and reflectance values were in certain cases similar to those of charcoal production sites. Also termite hills could possibly

Table 2
Accuracy assessment results.

Date	Total visual	Total semi-auto	Visual ∩ Semi-auto	Producer's accuracy	User's accuracy
18-Feb-11	735	660	472	64.2%	71.5%
03-Mar-11	685	523	496	72.4%	94.8%
19-Feb-13	1512	1113	991	65.5%	89.0%
23-Feb-13	275	228	180	65.5%	78.9%

Table 3
Number of sites detected for the entire study area respectively on 2011 and 2013 scenes.

Date	Site nos.	Date	Site nos.
18-Feb-11	8451	19-Feb-13	15,009
03-Mar-11	5658	23-Feb-13	3033
Total 2011	14,109	Total 2013	18,042

Table 4
Number of detected sites grouped by size. Sites detected solely on 2013 scenes, and not on 2011 scenes, are reported under "2013 only" column.

Site radius size	2011 (a)	2013 (b)	2013 only (c)	Difference (c − a)
2–3 m	7522	9358	7840	318
3–4 m	3743	4829	3835	92
4–5 m	1694	2450	1948	254
5–6 m	875	1107	906	31
6–7 m	233	276	227	−6
7–8 m	42	20	19	−23
Total	14,109	18,042	14,775	666

show as circular objects on the image, but these did not lead to commission errors, given that they have approximately the same color as the soil, and hence are discarded by the reflectance threshold. A high user's accuracy, and therefore relatively low commission error, means that the identified sites are actual sites; while a lower producer's accuracy, and thus higher omission errors, means that we identified less sites than really present. Given that our producer's accuracies are lower than our user's accuracies, we can expect our estimates of total charcoal production sites in the study area to be conservative. Although the accuracy may be increased further, the consistent approach used across all images allows for a reasonable interpretation of the changes in charcoal production sites between 2011 and 2013.

Changes in charcoal production (2011–2013)

Table 3 shows the number of sites detected for the entire study area on 2011 and 2013 scenes, respectively. A total of 3267 sites were detected on both images, meaning that a number of sites can still be detected after two or more years from their use. In fact, as Table 4 shows, 14,775 sites were detected solely on 2013 scenes, and hence built in the two-year period between March 2011 and March 2013. Detected sites were grouped by size, and a one meter reduction in site radius size was applied to account for some spreading out of the charcoal and ashes after the kiln is uncovered. The overall 4.5% increment in the total number of recent sites is mainly due to an increase in number of sites of small to medium radius, and results into an increase in overall charcoal production. The real increment between the two dates is higher as parts of those detected on 2011 images were actually built in previous years. Unfortunately this number cannot be quantified without images prior to 2011, which were not available for this study.

Fig. 3 shows the spatial distribution of charcoal sites in both years. Key production areas are concentrated in the central part of the study area and approximately in the same zones in 2011 and 2013. However, 489 new grids with charcoal production sites can be observed in 2013 across the study area, which mostly are low-intensity production sites (as judged from the amount of sites per grid). The changes are highlighted in Fig. 4. The comparison of the site distribution over the two-year interval highlights the areas affected by recent charcoal production activities, thus providing a spatial overview of changes in key production zones.

Smaller sites (3 to 4 m radius) are mainly concentrated within 5 km of agricultural areas (Fig. 5), which are also the more accessible ones as most settlements are located here. This could suggest that local population sells or otherwise delivers charcoal to local militant groups. As supported by local expert knowledge, an alternative explanation is that trees near agricultural areas were heavily logged in past years, not allowing for a sufficient coppice regeneration, and therefore leaving only smaller trees with less timber for charcoal production. The detected charcoal production patterns seem to support that the recent large scale charcoal production, as the one promoted by Al-Shabaab, concentrates first in areas with relatively high tree density and short distance from main roads, agriculture areas, and settlements. However, as tree cover diminishes, more remote areas are exploited as well as shown

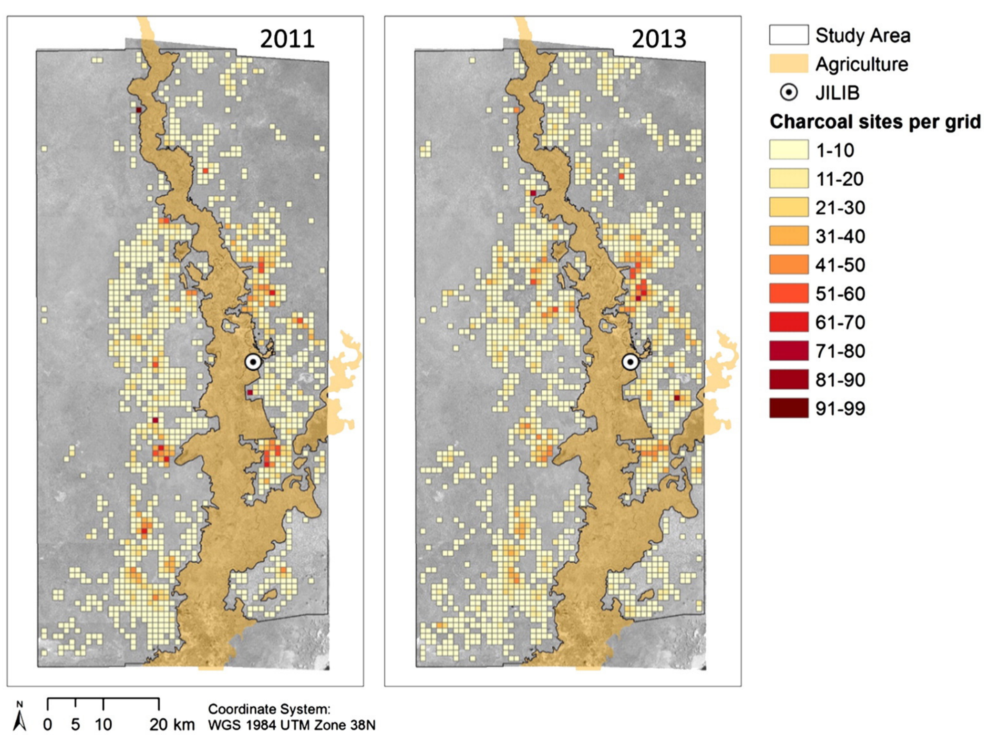

Fig. 3. Spatial distribution of charcoal production detected with the object-based classification using 2011 and 2013 WorldView-1 imagery. Charcoal sites are grouped by 1 × 1 km grid cells.

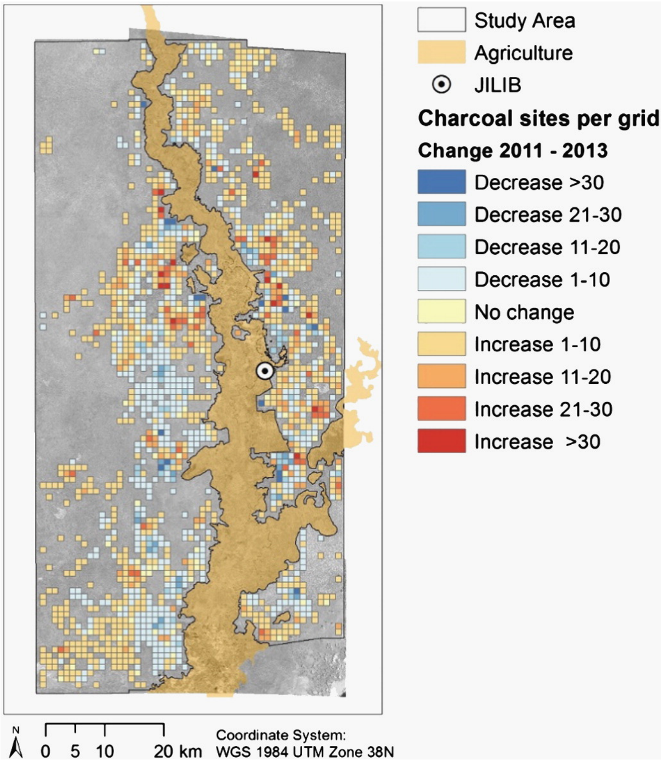

Fig. 4. Changes in the detected number of sites per grid (1 × 1 km) between 2011 and 2013.

by the trend of new sites in the northern part of the area, which is more remote from the charcoal export locations along the coast. The analysis of the results also supports our hypothesis that the charcoal production process in southern Somalia is carried out with a more 'industrialized' process involving the construction of numerous kilns, as indicated by the presence of some larger kilns compared to kilns built in other part of Somalia, which requires a large labor force to build the kilns and transport the charcoal, and the use of trucks for transport.

Google Earth contains very high resolution QuickBird and IKONOS imagery for the interval 2002–2005, covering about half of the study area. Through visual interpretation of these images we could detect only very few production sites. This finding is confirmed by the study of Rembold et al. (2013) who indicated that for a 60 km^2 subset of our study area no production sites were visible in 2006, and concluded therefore that tree cutting started between 2006 and 2010. The charcoal export intensification after 2010 observed by the UN (2012) matches our results, which show a high density in production sites for 2011 and 2013.

Estimation of wood volume used and tree loss related to charcoal production

Since precise information on vegetation composition and wood resources of the study area is not available, a range of literature-based values was used (see Methods section). This leaves the interpretation of the outcomes open to either conservative or more speculative conclusions. Table 5 shows a summary of mean values and corresponding standard deviations of dry wood used, charcoal production, and charcoal bags produced, as calculated for each site radius. For charcoal amounts, the mean and standard deviation are based on all possible combinations of the assumed low/high values of kiln height, volume air and other biomass, and timber density.

Table 6 presents the total wood volume and charcoal production estimates for the entire study area. These estimates are based on the sites that were identified uniquely on 2013 scenes, and exclude sites detected on both dates, as we cannot tell when those sites were built. We estimated that 372,000 ± 134,000 m^3 of total wood volume was used for charcoal production at these sites, corresponding to about 24,000 ± 9000 tonnes of charcoal produced and 876,000 ± 344,000 bags.

Finally, the estimated average tree loss rate for the study area, again only including sites uniquely detected on 2013 scenes, is 2.7% ± 1.1% considering a tree density of 3,400 per km^2 (Rembold et al., 2013). In

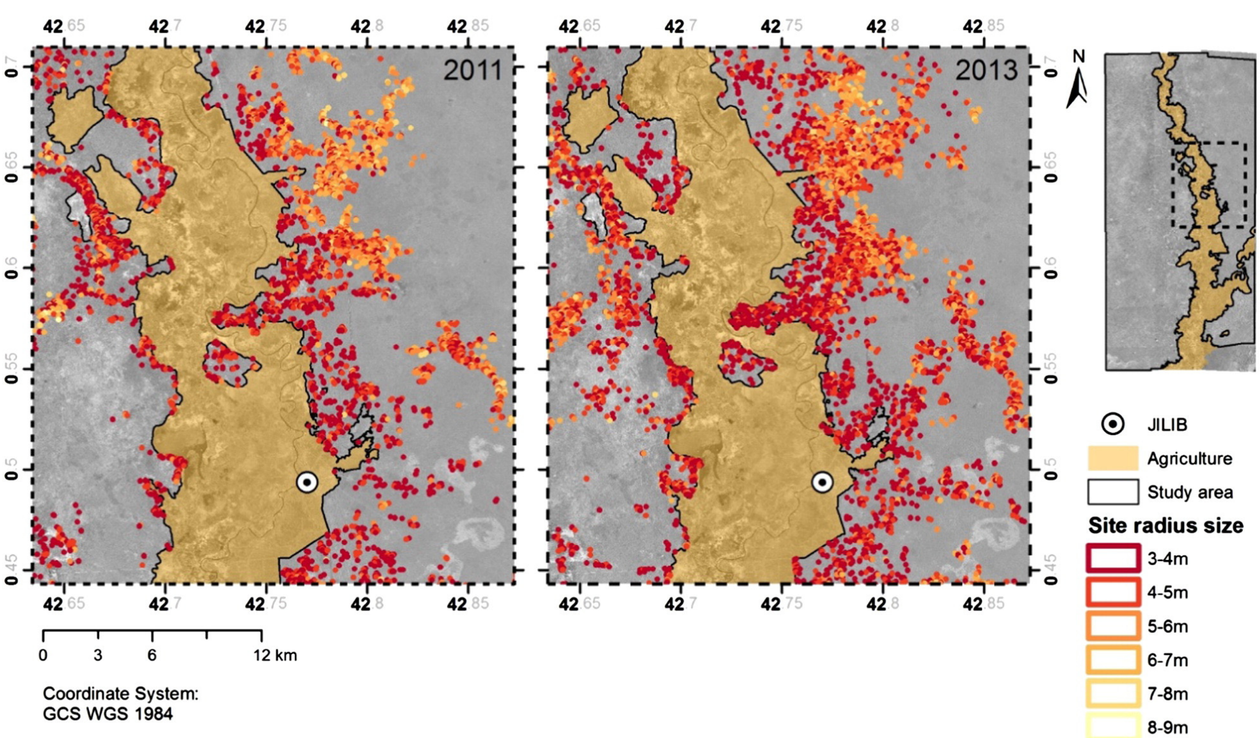

Fig. 5. Example of semi-automatically detected charcoal sites grouped by radius size.

Table 5
From kiln size to quantification of dry wood used, and charcoal and charcoal bags produced. Reported values are averages. To determine the mean and standard deviation we used all combinations of assumed low/high values for dry wood used, charcoal production, and charcoal bags produced, calculated for each site radius.

Site radius (m)	Dry wood mean (m^3)	Dry wood Stddev (m^3)	Charcoal mean (kg)	Charcoal Stddev (kg)	Bag mean (no.)	Bag Stddev (no.)
2	5.3	2.5	675	452	25	17
3	10.5	4.6	1329	846	49	31
4	17.8	7.5	2244	1398	83	52
5	27.2	11.2	3420	2108	127	78
6	38.6	15.7	4858	2976	180	110
7	52.2	21.1	6557	4001	243	148
8	67.8	27.2	8518	5185	315	192
9	85.5	34.2	10,740	6526	398	242

terms of number of trees, it means that an average of 438,000 ± 172,000 trees was cut down after 3 March 2011, out of the 15,980,000 trees potentially existing in 2006.

Studies conducted in other parts of Somalia formed the basis of the estimation of the parameter values used in this study. With the continued impossibility of conducting field data collection in southern Somalia, more accurate estimations could only be obtained by replicating the conditions found in the study area (i.e. building a series of kilns in the same way as in the study area, under the guidance of experts with local knowledge). The translation of charcoal production to tree cover loss followed the same assumptions presented by Rembold et al. (2013). Even the conservative figures provided by the present research (Table 6), taking moreover into account that the number of identified sites already offer a conservative estimate of the actual number due to the higher user's as compared to the producer's accuracy, highlight that the tree canopy is being lost at an alarming rate in the study area. In addition, the 'industrial' scale of current charcoal production could imply a lower conversion efficiency as compared to the 20% that we assumed, which would translate into even higher tree loss.

Although our study estimated tree cover loss based on identified charcoal sites, it was outside our scope to examine the longer-term impact of charcoal production on land cover. A large number of sites detected in 2011 were not visible anymore as sites in 2013 due to reasons like soil transported by wind, organic matter decomposition, and washing away of ashes. Natural regeneration capacity is generally low for arid and semi-arid woodlands, and over-exploitation often leads to durable negative environmental effects such as land degradation (Ndegwa et al., 2014). A UNEP report suggests that charcoal production in Somalia results in a constant net loss of vegetation, as growth rates of Acacia are very low and no reforestation is taking place (UNEP, 2005). While it is obvious that in a two-year time frame trees cannot mature, it would be important to perform longer-term monitoring of the tree cover at and around former charcoal production sites to evaluate if after five to ten years trees are able to establish again, and ideally understand also if the same valuable Acacia species are returning at those locations or if invasive undesired species establish themselves. Such monitoring could provide better insights in the regenerative capacity of the *Acacia–Commiphora* bushlands in areas that, as our study shows, are heavily affected by charcoal production practices.

Table 6
Estimate of wood volume used and charcoal produced after March 2011. Values in the table refer to sites identified uniquely on 2013 scenes (not detected on 2011 scenes). To determine the mean and standard deviation we used all combinations of assumed low/high values for dry wood used, charcoal production, and charcoal bags produced.

Site radius (m)	Number of sites (no.)	Wood vol. mean (m^3)	Wood vol. Stddev (m^3)	Charcoal mean (tonnes)	Charcoal Stddev (tonnes)	Bag mean (no.)	Bag Stddev (no.)
2–3	7838	114,519	46,667	7274	3353	269,411	124,199
3–4	3835	100,308	36,6433	6375	2533	236,114	93,805
4–5	1948	80,906	26,003	5145	1847	190,571	68,415
5–6	906	55,066	16,185	3502	1174	129,699	43,489
6–7	227	19,038	5242	1211	387	44,843	14,347
7–8	19	2106	553	134	41	4959	1535
Total	14,773	371,942		23,641		875,596	

Towards a national charcoal production monitoring system for Somalia

To detect charcoal production sites and the changes in their locations across a 4700 km^2 area in southern Somalia from high-resolution panchromatic imagery, a simple rule set for object-based image analysis was developed and applied in this study. The semi-automated procedure could objectively identify the majority of the charcoal production sites and accurately locate the main production areas, while avoiding labor-intensive visual image interpretation. Although panchromatic WorldView-1 scenes offer only a single spectral band and as a consequence may provide less information as multispectral imagery, for this study the multi-temporal WorldView-1 imagery coverage over a relatively large area could provide a first insight into regional-scale dynamics of charcoal production. An even better insight in these dynamics may be obtained with a higher frequency of image acquisition (ideally on a yearly basis, at the end of the main *Jiilaal* dry season). This could improve the capability of discerning old sites from recent sites and the detection of changes in production locations over time. Potentially, an increased availability of multispectral very high resolution imagery (e.g. WorldView-2) and information on spectral signatures of the main tree species used for charcoal production may eventually provide an analysis of tree composition at the regional scale and may allow analyzing the logging of individual large trees.

Although we assessed charcoal production changes for an unprecedented large area in Somalia, interest exists to monitor even larger areas. Al-Shabaab is reported to be the main actor actively involved in charcoal production (UN Security Council, 2011) and therefore a major cause of tree cover loss. Extending the analysis to other parts of the country, neighboring our study area, will result in a better overview of charcoal production zones and their changes, which could give indication of Al-Shabaab influence and movements in the region. Nonetheless, also other armed groups may potentially profit from the incomes of large-scale charcoal production, hence charcoal production monitoring should not be restricted to supposed Al-Shabaab territory. Moreover, given the importance of trees as a resource (ICRAF, 2014) and the expected climate change that may aggravate land degradation and drought vulnerability of Somali populations (Holleman, 2003), close monitoring of this resource in Somalia is needed. Ultimately this could also link to international programs like the Reduction in Emissions from Deforestation and forest Degradation (REDD) programs. This calls for the development and implementation of a charcoal production monitoring system for Somalia, and possibly for other countries in the region.

Our study contributes to the development of such a charcoal monitoring system, as we showed that detailed change analysis of large areas is possible with a time-efficient approach yielding a reasonable accuracy. The primary limitations when monitoring large areas with very high spatial resolution imagery include not only the development of generic and robust methods to be able to replicate interpretation in a consistent way, but also the cost and the availability of required data sets, and having the resources to purchase such data (Hansen et al., 2008). Wall-to-wall monitoring with WorldView-type imagery may not (yet) be achievable for the entire area of Somalia covered by woodland (about 340,000 km^2) in terms of image costs. An area-frame sampling approach (Gallego, 2004) could be a potential solution, where changes in charcoal production are only assessed for a number sample areas within the country. Rather than full random sampling, recent land cover maps could help in identifying areas with remaining high tree density, thus informing a stratified sampling scheme. The most recent wall-to-wall land cover map of Somalia was produced in 2002 from visual interpretation of Landsat TM (30 m resolution, freely available) images, acquired mainly in the year 1999 (FAO, 2002). This could be updated at a relative low cost and maintained up-to-date in future using for example the upcoming Sentinel-2 satellite (10 m resolution) or the already operational Landsat-8 (15 m), both freely available. Moreover, further study is needed to attempt 'up-scaling' (Hay et al., 2001) the charcoal production site detection from very high resolution imagery to somewhat coarser data (as offered e.g. by Sentinel-2 or RapidEye) to reduce image costs and increase coverage. Although spatial resolution is reduced, this imagery has more spectral information as compared to the WorldView-1 imagery used in this study, which could benefit their potential detection capabilities.

Conclusions

We could effectively detect charcoal production sites for a large area in southern Somalia based on 0.5 m resolution WorldView-1 imagery. The developed semi-automatic method identified individual sites and main production areas in 2011 and 2013, allowing for the assessment of changes. We could translate this into an indicative quantification of charcoal produced following a number of assumptions on kiln and tree parameters. This research contributed to the limited quantitative and spatial knowledge regarding charcoal-driven tree cover loss in southern Somalia by spatially showing the origin of the rapidly increasing amount of charcoal production and export. Despite the fact that the estimated 2.7% of tree loss refers to a very short period (2011–2013), it represents an alarming figure, in line with the 7.2% reported by Rembold et al. (2013) over the period 2006–2012. While further analyses to cover a longer period and even larger areas are recommended, the outcome of this research represents an important step towards the establishment of a reliable charcoal production monitoring system.

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