MONITORING OF AGRICULTURAL LAND CONVERSION WITH COPERNICUS SENTINEL SENSORS: CASE STUDY OF GAMBELLA STATE (ETHIOPIA)

GUIDO LEMOINE, FELIX REMBOLD
Joint Research Centre, European Commission, Italy
guido.lemoine@ec.europa.eu

Paper prepared for presentation at the
“2017 WORLD BANK CONFERENCE ON LAND AND POVERTY”
Abstract

Agricultural production in Africa needs to expand considerably for food self-sufficiency to keep up with population growth and differentiating dietary needs. Expansion of agricultural cultivation is already ongoing and, in some regions, has led to controversy about the scale, manner and impact of land allotment policies. The recent introduction of the European Union's Copernicus Sentinel-1 and -2 sensors has added global monitoring capacities in the 10-20 m spatial resolution domain. Sentinel data are available under a "full, free and open" license. Sentinel sensors combine Synthetic Aperture Radar (SAR, Sentinel 1) and multi-spectral (Sentinel-2) observation capacities with a 6 day revisit (Sentinel 1A and 1B) and a 5 day revisit (Sentinel 2A and Sentinel 2B (Q2/2017)), respectively. We illustrate the use of Sentinel data for the delineation of large land development in Gambella State (Ethiopia), where we have been able to identify a total of 110,000 hectares of recent developments. We will discuss how we use the Google Earth Engine cloud computing environment to continue the monitoring of Gambella state and expand into other areas where land deals have been identified.

Key Words: land conversion, agriculture, monitoring, Sentinels, remote sensing
Introduction

Large scale land acquisition or leasing in developing countries is a sensitive issue with significant economic and food security impacts. More intensive/productive agricultural systems are being implemented over large areas by private companies for export, with the idea that revenue may contribute to improve food security of the countries. However, local communities may not always benefit from that because of insufficient compensation schemes, and are often subject to negative impacts such as land-related conflicts and the loss of their main source of income (JRC 2013). The “Land Matrix” Project is monitoring the metadata of the best known of these transactions in the world and records them in an online database. According to the Land Matrix Ethiopia is in the top 10 largest target countries for large scale investments and was ranked 7th in 2010 (Land Matrix 2010). In July 2009 the government of Ethiopia had reportedly marked out 1.6 million hectares of land (extendable to 2.7 million ha), for investors willing to develop commercial farms (Cotula, 2012).

The controversial aspects of large scale land transfers (LSLT) in a country like Ethiopia are underscored by the fact that the country is a net food importer and has in the past been affected by severe famines. According to the Economist in Ethiopia Saudi investors alone are spending 100 million USD to raise cereals (wheat, barley and rice) on land leased to them by the government. The investors are exempt from tax in the first few years and may export the entire crop back home. At the same time Ethiopia is a net food importer and the World Food Programme has spent almost the same amount as investors (116 m) providing 230 000 tonnes of food aid between 2007 and 2011 to the estimated 4.6 million Ethiopians threatened by hunger and malnutrition (The Economist, 2012). Also, deforestation and irreversible destruction of wet lands are major environmental threats facing Ethiopia and few agricultural investment projects had an environmental impact assessment (EIA) as required by law (World Bank 2011). Much of the land that has been given to investors (and that is marketed as available) is not presently under cultivation, rather much of it is covered by woodland or forest (OI 2011).

In Ethiopia, only 23 of the 406 projects (5.7 percent) involve foreign investors, and more than half of projects are less than 1,000 ha in size. Still, five large projects make up half the area leased out by the government. Several reports have also highlighted that for LSLT in Ethiopia there is often a large gap between the initial intentions declared at the time of contract signature and implementation over the following years. Despite the existence of rules for canceling concessions, effective implementation is often slow and large amounts of what is often a country’s most productive land may be under-utilized. For
example, in the Amhara region of Ethiopia, field visits confirmed that only 16 of 46 projects in the inventory of large-scale agriculture projects were used as intended (Tamrat 2010). In other projects, the land was either used for other purposes (such as forest clearance) or simply rented out to smallholders in explicit contravention of contract.

Due to the risk and controversies that accompany LSLT and of which some have been laid out in this introduction, monitoring of land use change and effective implementation of projects is crucial. This is often difficult for remote areas and also because initial mechanized interventions can be perceived as the start of project implementation, but are often not followed by longer term development.

**Land conversion in Gambella**

In this report we are concentrating in particular on the Gambella state of Ethiopia, which is reported as one of the areas with the highest concentration of LSLT and at the same time with the scarcest information available.

The study area, Gambella state in western central Ethiopia (Figure 1) has been chosen because reports on controversial land deals (OI, 2011), leading to a range of socio-economic issues in the region. The many factors reported as contributing to controversy include the following: most land conversion in Gambella is stimulated under a federal investment programme for domestic and foreign investors. The set-up suffers, amongst others, from non-transparency of financial deals, absence of impact assessment, monitoring and enforcement of rules, absence of land tenure and compensation and disregard for traditional land rights including the forced displacement of people, immediate and future environmental degradation. Information on land deals in Gambella is incomplete and suffers from large discrepancies between claimed deals and practice. Most emphasis has been given to large foreign deals (for Gambella, Saudi Star Ltd and Indian Karuturi), but information on domestic deals remains largely unclear.

A summary of figures for a total of 829200 hectares of foreign land deals in Gambella (OI, 2011) is listed as:

- 300,000 ha for Karuturi (later revised to 100,000 ha) for rice, palm oil, maize, soybean
- 25,000 ha Ruchi Soya (India) for soybean
- 10,000 ha Saudi Star (Saudi-Arabia) for rice
- 27,000 ha BHO India for biofuel seeds
- 10,000 ha Sonnati Agro Farm (India), rice, pulses, cereals
A key objective of the study is, therefore, to try to verify reports of large scale land conversion in the region and to map and enumerate the spatial extent of current large scale agricultural operations and compare the result to a reference situation. Based on our findings, we propose a method to monitoring progress in land conversion on a regular basis.

A reference to the woreda (district) names used in this report is given in Figure 2 against a backdrop of OpenStreetMap (OSM). Administrative boundaries in OSM (and other online map data, such as Google Maps) are not exactly the same as those in the GAUL data set, from which our administrative boundaries are sourced. In particular, the lower half of the southern Dima woreda is not included in other sources. The OI, 2011 reference states a smaller overall area for Gambella state (2.58 Mha) than outlined by GAUL (3.08 Mha).
The topography of Gambella state shows the abrupt transition from flat lowlands in the west (400 masl) to the Ethiopian Highlands in the East (up to 2200 masl). The precipitation regime is a reflection of this difference in altitude, showing a northwest-to-southeast gradient from 800 mm/yr to 2100 mm/yr on the plateaus (2011-2016 average). The rainfall distribution is strongly seasonal, with a dry period between December – March and a peak rain season in May – August.

**Data and Methods**

**Data**

Earth observation can be used to evaluate and map how much land is effectively converted by the contracted deals and later on to monitoring their implementation and maintenance. Due to the availability of satellite imagery at different scales, it is possible to assess land use changes at the woreda (district) level for the whole Gambella state, but also to map single investments at a high level of detail. In
particular the introduction of Sentinel sensors under the EU funded Copernicus programme is enabling new capacities to monitoring large areas across the globe at unprecedented spatial detail and temporal frequency. The consistency of the monitoring efforts is especially enhanced through the availability of SAR (Synthetic aperture radar), which acquires data independent from atmospheric or sun light conditions. The use of these new capacities are especially relevant in monitoring of land conversion processes, and, in the case discussed in this report, for agricultural land conversion or forest or rangeland areas. The latter is important in the context of food security analysis which, apart from an interest in actual production, is dealing with long term trends in food and feed productivity and is among other factors dependent on natural resources availability and management.

With the introduction of the Sentinel satellite by the Copernicus program, the availability of high resolution (10-30 m resolution) satellite imagery under free and open license conditions has significantly expanded. Previously, only US Landsat imagery available was freely available. The Sentinels introduce free access to 10 m resolution Sentinel-1A SAR (S1A) and optical and infrared data from Sentinel-2A (S2A). SAR has the advantage that it works under all weather conditions and independent from sun illumination (i.e. day and night). The revisit frequency of S1A’s 12 days has recently been doubled with the launch of the Sentinel-1B twin (operational since 26 September 2016). SAR coverage over Africa since April 2015 has been densest over geophysical active areas, which include Ethiopia. Sentinel-2A is operational since August 2015, and has a 10 day repeat cycle (to be doubled to 5 days revisit after the launch of Sentinel 2B on March 7, 2017). As an optical/infrared passive instrument, data acquisition is dependent on illumination and atmospheric conditions, however. This is also the case for Landsat sensors. A reliable monitoring methodology should, therefore, be based on the consistent availability of Sentinel 1 SAR data, complemented with occasional optical sensor data from S2A (and Landsat). This is particularly true if time constraints are not too critical, as in seasonal land use change updates.

In this study, we have not made use of any ground observations in the study area (other than contextual photographs from reports and web sources). This is an obvious drawback and the main reason why we do not attempt to distinguish individual crop types in our land conversion delineation exercise.

**Google Earth Engine**

Access to global free and open data at high resolution requires significant computing storage and processing resources. A recent trend, often hailed as the “new Big Data paradigm”, is to move large data storage and processing towards cloud solutions. Cloud solution providers facilitate access to their
hardware infrastructure to run data processing algorithms in parallel against these large data sets. A prime cloud computing solution in the geospatial use domain is Google Earth Engine (Google, 2017). GEE provides registered users access to most of the free and open access data catalogues, including MODIS, Landsat, Sentinel-1 and Sentinel-2 data, at full resolution, which are stored in Google’s Cloud storage infrastructure. Other open access raster data resources, such as SRTM DEM (Digital Elevation Model) at 1 and 3 arc sec resolution, gridded rainfall estimates (CHIRPS), Global Forecasting System atmosphere modeling outputs and global land cover or thematic classification outputs are also available as catalogues. Sentinel-1 data is included as geocoded calibrated backscattering coefficients and Sentinel-2 as so-called top-of-atmosphere reflectance. GEE also facilitates integration of feature data sets, such as administrative boundaries, digitized topography. A key feature of GEE is the possibility to integrate access to global data sets with programmable processing logic that is made available as a library of routines. The user can combine data selections and library functions in scripts that define pertinent workflow that may result in a raster output, for instance, a classification result, or which can be reduced to tabular format, for instance, spatial statistical aggregates. GEE has been used extensively in the reported analysis.

Methodology

We use the Global Land Cover layer (GlobeLand 30) 2010 as reference (Chen et al., 2015). This layer is based on analysis of multi-annual Landsat imagery with 30 m resolution. Although the quality of the Globeland30 is variable, esp. over the humid tropics, it is relatively well representing Gambella land use, based on a comparison to selected 2008-2010 Landsat imagery. Because the main large investments as well as smallholder cultivation existing at that time according to the Landsat images we verified, are well mapped, we assume that the product can be reasonably used as a reference for the year 2010.

In this study, we try to distinguish between several types of land conversion processes:

Shifting cultivation: traditional native agricultural cultivation on the basis of 3-7 years periods, converting natural land use to agriculture (slash and burn) and then abandon for nearby plots after fertility of the soil is decreasing. Small scale and often combination of different cultivars near river floodplains and maize and sorghum cultivation on higher ground, combined with forest use and fisheries. Most common along rivers in Gambella state and in small areas in the eastern forested area.
Smallholder cultivation: permanent non-mechanised cultivation in (very) small plots, combined with grazing on (common) land and exploitation of natural land use. Limited to eastern area near Suc-suc.


Irrigated arable crops: like rainfed, but with use of irrigation, enabling intensive crop production, across seasons. Requires dedicated irrigation and drainage infrastructure, high initial investment, guaranteed access to water.

Clearance: intermediate stage between natural vegetation state and intentional crop cultivation. Land is cleared of natural vegetation and land preparation work for cultivation carried out (e.g. leveling, access roads, irrigation infrastructure). However, land may also be left fallow after clearance (e.g. vegetation primarily cleared for charcoal production, but no intention to develop cultivation). Since we primarily map larger clearings, this class is an indicator for future extension of rainfed and irrigated cultivation types.

Plantation: permanent cultivation of multi-annual crops (e.g. coffee, tea, banana) or agro-forestry.

We use the group term “mechanized agriculture” to include rainfed and irrigated arable crop cultivations that require regular or continuous modern farm machinery and equipment. A typical characteristic of “mechanized agriculture” in the satellite imagery is that it can be detected from the regular shape and the large size of the land conversion. Also, plots that are already under cultivation typically have clear subplot boundaries (for different crop types) and may show evidence of road and irrigation infrastructure.

With the data selection readily available in GEE, a core part of the analysis was related to the detection and delineation of the (mechanised) agricultural activities. Example classes are illustrated in Figure 12. Delineated areas are attributed as follows:
Status: one of 6 cultivation types defined above. Shifting cultivation is used only sparsely, as this is difficult to detect in short time series. For smallholder cultivation, only a number of clear cases were selected. This class is likely larger, esp. in the Mengesh, Godere, and Dima woredas. This study was somewhat biased towards the detection of new mechanised cultivation types.

Intensity: for each polygon outlining a cultivation type, the total area under cropping is estimated as a percentage of the total area digitised. For intensive and plantations this tends to be (near) 100%, while clearance only is (near) 0%. Intensity can be used as a weight to estimate total cultivated crop area.

Irrigated: yes (1) or no (0), based on criteria that suggest developed irrigation infrastructure, such as regular plot size, canals, flatness of the terrain. Irrigation from [groundwater] pumping and pivots is not directly detectable in the imagery used.

The interpretation of the attributes is primarily based on an analysis of the Sentinel 1A SAR data, which is composed as 2 time composites for the periods April-October 2015 and November 2015-June 2016 (Figure 3). Both the radiometric variation in the time series as well as the detection of regular structures is a good indicator for agricultural activities. In Figure 4, two examples are shown together with the delineated outlines of the cultivation. Selected Sentinel-2A and Landsat 8 images available of the area are used to confirm shape and occurrence of cultivation activities. The Google background imagery is also helpful for interpretation, although it is typically not showing recent developments when imagery is several years old. The presence of settlements, roads and canals and vicinity to nearby existing agricultural developments is often a precursor for the detection of additional developments. By comparing between S1 composites for the two periods we can also demonstrate the feasibility to highlight ongoing land conversion on a 3-6 month revisit basis.
Figure 3. Sentinel 1A backscattering coefficient composite for the period April-October 2015 (top) and November 2015-June 2016 (bottom) overlaid on the Google Maps background in Google Earth Engine. Bright white areas are dense forest (east). The large wetlands straddling Jor and Akobo (west) stand out as bright green. Low density forest and non-forest covers of the central woredas show up as intermediate colours, representing areas with open vegetation structures (grassland, agriculture, shrubland). Drying out of vegetation is causing the reddish colours in the latter composite, which starts at the end of the rain period.
Figure 4. Saudi Star Ltd. rice cultivation near Abobo dam(right). This area of 6500 ha stands out in the Sentinel 1A SAR composites due to its very regular structure, indicative for extensive irrigation infrastructure, and its bright colours, which relate to different rice cultivars at various stages in the growth cycle. On the right is a 12,800 ha development area in Itang woreda, which is a mix of cleared areas, some of which are already cultivated, and areas that are not yet cleared. This appears to be a recent clearing, and it is not yet evident whether the remainder will be cleared for cultivation.

Results and Discussion

The digitised outlines are mapped in Figure 5. The map shows extensive development in Itang, Gambella, Abobo and (less so in) Goge woredas. Clustering of intensive and partial development lots illustrate ongoing expansion. All the expansion includes conversion to mechanized agriculture type. Clearings are usually associated with, at least partial, cultivations. The few cases of “clearing only” are small, and may either be the start of a large development, or may be cases that were abandoned. Similarly, partial developments may be cases for which only a fraction is used for agriculture at the moment and for which further cultivation is either in progress or may have been abandoned. Our data suggest that there are few cases where land is cleared without any further agricultural use (e.g. for charcoal production only). However, in several cases where we expect to detect crop cultivation, we may actually pick up natural regrowth (e.g. initially as grass or short vegetation). Our SAR time series is too short to distinguish, for instance, between establishment of permanent crops (e.g. plantations) and natural regrowth. In these cases, the level of uncertainty in determining successive land abandonment is larger. We expect a better delineation with continued time series, esp. where multi-season cultivation is evident.

No development was detected in wetland areas (GWLR, Jor, Akobo), which is likely related to absence of infrastructure and drainage issues. We have detected the establishment of (road) infrastructure in Jikawo and Wantawo woredas, but no associated land clearance (yet).
In the densely forested east detected areas are mostly traditional small holder and shifting cultivation, with only few new developments, which is likely related to poor suitability for large scale development.

In numbers, we can summarize results as follows:

- Total area Gambella: 3.08 Million ha (compares to 2.56 Million ha in OI (2011), related to exact outline of Dima)
- Total area digitized as agriculture: 113,600 ha ~3.6% of total area.
- Intensive: 66.6 kha (of which 35.6 kha irrigated)
- Partial: 26.1 kha (of which 11.6 kha cultivated)
- Total area cultivated: 89.8 kha (taking into account what is actually cropped inside the partial class)

For detailed numbers at Woreda level see Table 1.

Table 1. Digitized agricultural area size (in 1000 ha) for Gambella State woredas

<table>
<thead>
<tr>
<th>Woreda</th>
<th>GLC30 2010)</th>
<th>2016</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abobo</td>
<td>10.8</td>
<td>29.8</td>
<td>Intensive, with irrigation (from Abobo dam). Pre-existing and new agriculture in this area is mechanized.</td>
</tr>
<tr>
<td>Dima</td>
<td>0</td>
<td>9.1</td>
<td>Primarily smallholder cultivation, some small new development</td>
</tr>
<tr>
<td>Gambella</td>
<td>0.1</td>
<td>16.2</td>
<td>Intensive, clearing ongoing. Mechanised.</td>
</tr>
<tr>
<td>Godere</td>
<td>5.4</td>
<td>5.4</td>
<td>Not actually digitised in 2016. Primarily smallholder cultivation, with no major new development compared to GLC30</td>
</tr>
<tr>
<td>Goge</td>
<td>0</td>
<td>12.8</td>
<td>Isolated intensive operations, clearing ongoing. Mechanized.</td>
</tr>
<tr>
<td>Itang</td>
<td>0</td>
<td>28.4</td>
<td>Intensive operations, clearing ongoing. Mechanized.</td>
</tr>
<tr>
<td>Jikawo</td>
<td>0</td>
<td>5.3</td>
<td>Single large clearing</td>
</tr>
<tr>
<td>Mengesh</td>
<td>4.9</td>
<td>6.6</td>
<td>Existing plantations (arboriculture), some minor new development, additional scattered smallholder cultivation not digitized.</td>
</tr>
</tbody>
</table>

|          | 21.2 | 113.6 | About 3.6% of Gambella state |

In the GWRL, Jor, Lare, Akobo and Wantawo woredas, no detectable agricultural activities were found.
Figure 5. Map of detected agricultural production areas, grouped by estimated type, based on the analysis of 2015-6 Sentinel-1 and Sentinel-2 image composites.
Conclusions

We have demonstrated that, with the new and continuous availability of Sentinel sensor data from S1 and S2, an operational land conversion monitoring activity is now feasible, even over areas where collection of optical data is challenging due to persistent cloud cover. While it is possible to follow developments since the start of operations of the S-1A instrument (April 2014) it is more difficult to go back in time before that. Should backdating be required, a selection of a mix of open access (e.g. historical ENVISAT) or commercial archive data (e.g. Radarsat, SPOT) can be considered.

We showed that it is relatively straightforward to delineate large scale land clearings and successive (mechanised) agricultural cultivation. With the presented methodology it is possible to map both land use conversion at the scale of the whole region, as well as outline in detail single large land investments and follow their expansion over time. Identification of smallholder and shifting cultivation practices is more challenging. On the other hand, the latter types of cultivations do not seem to be subject to rapid extension.

The total area calculated to be under mechanised cultivation in Gambella state is in the order of 110,000 ha. This is a significant extension compared to 2010 (in the order of 20,000 ha). The reference (OI 2011) stated that 170,000 ha were included in deals known at the time (following the downwards revised extent of the Kuratari lease). Our figures show that only two thirds of this area is under active agricultural use or under conversion. However, even if the total areas involved are smaller, the pattern of existing cultivations and neighbouring land clearing suggests that the land conversion process is in full swing. Our analysis has also shown that there are potentially other areas, in particular in the Gambela, Goge, Akobo, Jikawo and Wantawo woredas that are physiographically similar to the areas already under development and, therefore, candidate areas for detailed monitoring.

There are several factors that may influence further expansion. For instance, actual prices for agricultural commodities are well below half the 2008-2009 levels that triggered the current land conversion deals. Thus, from a pure commodity market perspective, growth in new investments in the more challenging production environment in Gambella may be expected to slow down. However, with the demand for food driven by an increasing world population and changing diets, interest and competition for fertile land is on the rise. Also, ongoing infrastructure development and scaled up agricultural activities in the Itang, Gambela and Abobo woredas, may create better investment opportunities. All these aspects suggest continuing a regular (e.g. semi-annual or annual) monitoring activity to understand spatial patterns and
trends in the expansion (or possible contraction) of these land conversion processes and to start addressing environmental impact aspects.

Such a monitoring activity is best served if it can be combined with the collection of other relevant information, such as the better characterization of the detected land development activities through ground surveys, detailed delineation of infrastructure, better characterisation of rainfed and irrigated cultivations, re-settlement activities and information on the socio-economic and environmental impacts. Obviously, the developed methodology can be applied in other (Ethiopian) contexts where land conversion is an issue, especially in those areas in which large scale development is also reported to take place at a significant scale (e.g. Oromia, SNNPR, Benishangul states).

A key shortcoming in our study is the impossibility to implicitly link the detected land conversion process to the socio-economic and environmental impact on the ground. The reference (OI, 2011) provides many details on the, mostly negative, impacts. Our data is, however, not detailed enough to understand replacement of native cultivation practices, esp. those that impact on traditional land use other than settled cultivation practices. Recent news items highlight that the land conversion topic has become very sensitive, both inside and outside Ethiopia. We expect major benefits in terms of verifying and extending the methodology from collaboration with other projects and partners that are actively promoting best practice in land tenure and responsible agricultural investments, including the (Ethiopian) government agencies. Open access to the relevant data sets and a wide choice of technical solutions to process the data at scale, which include open source platforms, are instrumental to local capacity building to help anchor long-term monitoring efforts at the most relevant actors.

References


