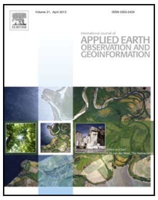
International Journal of Applied Earth Observation and Geoinformation 58 (2017) 225–233

Contents lists available at ScienceDirect

International Journal of Applied Earth Observation and Geoinformation

journal homepage: www.elsevier.com/locate/jag



Mapping the expansion of galamsey gold mines in the cocoa growing area of Ghana using optical remote sensing

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ARTICLE INFO

Article history:
Received 7 October 2016
Received in revised form 26 January 2017
Accepted 8 February 2017

Keywords:
Gold mining
Galamsey
Cocoa
Pollution
UK-DMC2
Change detection

ABSTRACT

Artisanal gold mining (galamsey) and cocoa farming are essential sources of income for local populations in Ghana. Unfortunately the former poses serious threats to the environment and human health, and conflicts with cocoa farming and other livelihoods. Timely and spatially referenced information on the extent of galamsey is needed to understand and limit the negative impacts of mining. To address this, we use multi-date UK-DMC2 satellite images to map the extent and expansion of galamsey from 2011 to 2015. We map the total area of galamsey in 2013 over the cocoa growing area, using k-means clustering on a cloud-free 2013 image with strong spectral contrast between galamsey and the surrounding vegetation. We also process a pair of hazy images from 2011 and 2015 with Multivariate Alteration Detection to map the 2011–2015 galamsey expansion in a subset, labelled the *change area*. We use a set of visually interpreted random sample points to compute bias-corrected area estimates. We also delineate an indicative impact zone of pollution proportional to the density of galamsey, assuming a maximum radius of 10 km. In the cocoa growing area of Ghana, the estimated total area of galamsey in 2013 is 27,839 ha with an impact zone of 551,496 ha. In the change area, galamsey has more than tripled between 2011 and 2015, resulting in 603 ha of direct encroachment into protected forest reserves. Assuming the same growth rate for the rest of the cocoa growing area, the total area of galamsey in 2015 is estimated at 43,879 ha. Galamsey is developing along most of the river network (Offin, Ankobra, Birim, Anum, Tano), with downstream pollution affecting both land and water.

1. Introduction

Gold mining in Ghana (Africa) is a complex system broadly divided into two groups, (i) large-scale mining concessions (modern surface/underground mining) and (ii) small-scale mines (artisanal surface mining) also called *galamsey*. The former contributes significantly to the overall economy of the country through fiscal revenue (Fonseca, 2004). However, they have little interaction with the local economies, they often lead to forced relocation of communities and are an undeniable source of environmental pollution (Aragon and Rud, 2013). In comparison, even though it is mostly illegal (Teschner, 2012), galamsey brings direct income to the miners and their families, and stimulates local trade related to mining (Amankwah, 2013). Unfortunately, as it is mainly surface mining, it results in significant destruction of natural vegetation and farm land, removal of soil, and diversion of water bodies. The mining process also leads to dust pollution, water pollution from increase in sediments (Kusimi et al., 2014) and the introduction of mercury which also contaminates soil (Serfor-Armah et al., 2004). In 2011 the Ghana Water Company Limited was forced to temporarily stop treating water because the Birim river was too polluted to be treated for domestic use (Amankwah, 2013).

Gold and cocoa are the backbone of Ghana's exports, recording respectively US$ 4,388.06 million and US$ 2,612.87 million which together account for 53.0% of total export receipts in 2014 (ISSER, 2015). Unfortunately the two activities struggle to coexist (Boateng and Codjoe, 2014). First, gold and cocoa are competing for land and labour – cocoa land is converted to mining and/or farmers abandon cocoa for trying their chance in neighbouring galamsey. Gold mining is favoured as it can provide quick profit compared to the poorly-paid seasonal cocoa activity. Second, the pollution from galamsey is reported to affect cocoa yield – farmers observe early fall of immature pods, wilting, and yellowing of leaves in plantations close to mined area (Boateng and Codjoe, 2014). Nonetheless, galamsey is also reported to have positive impacts on the cocoa activity. Rather than abandoning their farm, some farmers earn money from gold mining during the off-farming season and reinvest it in farming through hiring of labour and purchas-

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http://dx.doi.org/10.1016/j.jag.2017.02.009
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ing of agrochemicals otherwise unaffordable (Hilson and Garforth, 2013; Okoh and Hilson, 2011).

So far, most of the research on the galamsey problem in Ghana has relied on local evidence of the negative impacts of mining such as interviews of farmers (Boateng and Codjoe, 2014), unsafe concentration of mercury in samples of water/soil (Serfor-Armah et al., 2004; Armah et al., 2010) and in human blood/urine (Adimado and Baah, 2002), and occurrence of diseases (Opare et al., 2012). Remote sensing has been used to explore land use and land cover changes related to gold mining in local mining areas (Basommi and Guan, 2015; Basommi et al., 2015; Manu et al., 2004; Kusimi, 2008). These studies looked at broad class changes (Open Savannah, Closed Savannah, Bare areas, Settlements, Water bodies) after individual classification (using ISODATA or Maximum Likelihood) of multi-date Landsat images. Overall, the mining activity was associated with conversion of savannah areas into bare ground and settlement over periods of about 10 years, but none of these studies has delineated the mining areas. In regions of the Brazilian Amazon forest, artisanal gold mining has been mapped using cloud-free Landsat images. Almeida-Filho and Shimabukuro (2002) used a postclassification change detection approach based on image segmentation and *k*-means clustering, and Asner et al. (2013) used the Carnegie Landsat Analysis System-lite (CLASlite). Almeida-Filho and Shimabukuro (2000) also showed that mining areas could be identified from Synthetic Aperture Radar (SAR) images from JERS-1. In comparison, there are currently no reliable data on the location and the extent of galamsey in Ghana (Aragon and Rud, 2013). A timely and comprehensive map of galamsey is necessary to measure the extent of the problem, and to design efficient ground measurement campaigns to appraise the magnitude and effects of the pollution. Monitoring the evolution of galamsey is also valuable for the inter-ministerial task force against illegal mining (created in May 2013 by the President of Ghana, John Dramani Mahama) to better target their intervention (arrest of illegal miners, seizing of mining equipment).

In this paper, we use multi-date optical images acquired by UK-DMC2 to (i) map the extent and evolution of galamsey in southern Ghana from 2011 to 2015, and (ii) provide a preliminary assessment of the potential extent of pollution. UK-DMC2 is a British multi-spectral imaging satellite part of the Disaster Monitoring Constellation, operating in green, red and near infrared at 22 m resolution (Table 1).

2. Methodology

2.1. Data and study area

The *study area* (Fig. 1) was selected to cover the cocoa growing area of southern Ghana where most of the galamsey is concentrated. While northern Ghana is hot and dry, the cocoa growing area is hot and wet, prone to cloud cover and haze, particularly during the rainy season from April to mid-November. The MODIS cloud fraction product (Platnick et al., 2003) shows the study area had an average cloud fraction of 0.83 in 2015, with a minimum of 0.53 in December. A search of archive imagery between 2011 and 2015 from the Landsat mission only returned one cloud-free but hazy Landsat-8 images from 11 January 2015. Thick cloud cover and/or groups of scattered clouds made the other Landsat images unusable, even for multi-temporal compositing. Alternatively, a search of archive imagery from UK-DMC2 for the same period found three usable images of varying quality – 19 January 2011, 1 January 2013, 13 January 2015. The image from 2013 was cloud free and was used to map the total area of galamsey within the study area. The 2011 and 2015 images, used to map the 2011–2015 galamsey expansion, had a limited extent compared to the 2013 image and 29% of the overlap image (mainly in the southeast of the overlap), affected by thick haze, was removed during the change detection analysis. Consequently, the mapping of the galamsey expansion only covers 38% of the study area, referred as the *change area* (Fig. 1).

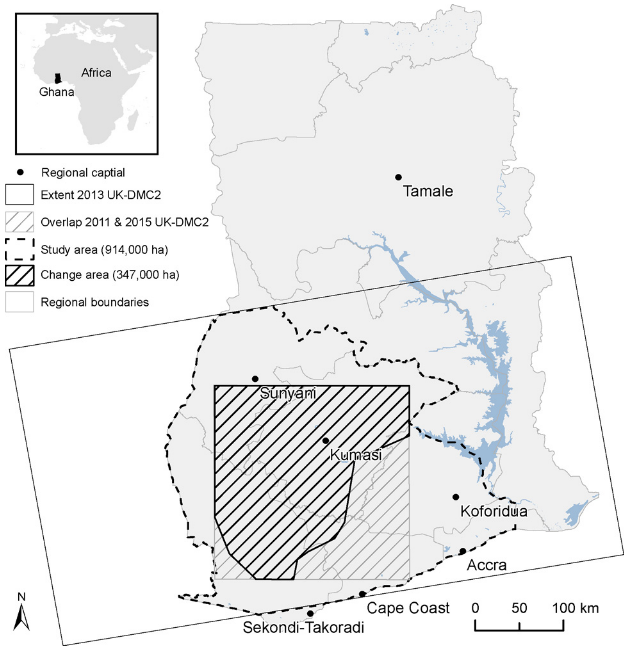

Fig. 1. Study area in southern Ghana with extent of the 2013 UK-DMC2 image and overlap area of the UK-DMC2 images from 2011 and 2015. The map of galamsey in 2013 covers the whole study area. Because of haze, the map of galamsey expansion only covers 38% of the study area, labelled change area.

Table 1
Technical characteristics of UK-DMC2 L1T product.

Resolution	22 m
Swath	660 km
Spectral bands	Green (0.52–0.62 μm) Red (0.63–0.69 μm) NIR (0.76–0.9 μm)
Bit depth	8 bit
Geometric RMS error	11–16.5 m
Signal to noise ratio	100:1

In the DMC imagery, galamsey appears as ribbons of highly reflective land, along river channels, with strong spectral contrast to the surrounding vegetation (Fig. 3). Spectrally separating galamsey from areas of settlements is difficult as both contain bare soil, and the pixel size is too coarse to utilise the image texture.

2.2. Total area of galamsey in 2013

The total area of galamsey was mapped using unsupervised classification of the UK-DMC2 L1T image acquired 1 January 2013 and visual interpretation of Google Earth© imagery (Fig. 2(a)). We did not use supervised classification as galamsey is a relatively low proportion of the study area, thus visual interpretation of a large number of non-galamsey pixels would have been required to collect a representative sample (Plourde and Congalton, 2003).

The image was first subset to the study area and the original Green, Red, and Near Infra-Red bands were converted to top of atmosphere reflectance according to the method in Crowley and Mackin (2008). A Normalized Difference Vegetation Index (NDVI) band was added as a new image layer to the reflectance bands to improve the spectral differences between vegetated and non-vegetated surfaces. We progressively separated galamsey from other land covers through two successive unsupervised classifi-