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Multi-scale 46-year remote sensing change detection of diamond mining and land cover in a conflict and post-conflict setting

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A B S T R A C T

The town of Tortiya was created in the rural northern region of Côte d'Ivoire in the late 1940s to house workers for a new diamond mine. Nearly three decades later, the closure of the industrial-scale diamond mine in 1975 did not diminish the importance of diamond profits to the region's economy, and resulted in the growth of artisanal and small-scale diamond mining (ASM) within the abandoned industrial-scale mining concession. In the early 2000s, the violent conflict that arose in Côte d'Ivoire highlighted the importance of ASM land use to the local economy, but also brought about international concerns that diamond profits were being used to fund the rebellion. In recent years, cashew plantations have expanded exponentially in the region, diversifying economic activity, but also creating the potential for conflict between diamond mining and agricultural land uses. As the government looks to address the future of Tortiya and this potential conflict, a detailed spatio-temporal understanding of the changes in these two land uses over time may assist in informing policymaking.

Remotely sensed imagery presents an objective and detailed spatial record of land use/land cover (LULC), and change detection methods can provide quantitative insight regarding regional land cover trends. However, the vastly different scales of ASM and cashew orchards present a unique challenge to comprehensive understanding of land use change in the region. In this study, moderate-scale categories of LULC, including cashew orchards, uncultivated forest, urban space, mining/ bare, and mixed vegetation, were produced through supervised classification of Landsat multispectral imagery from 1984, 1991, 2000, 2007, and 2014. The fine-scale ASM land use was identified through manual interpretation of annually acquired high resolution satellite imagery. Corona imagery was also integrated into the study to extend the temporal duration of the remote sensing record back to the period of industrial-scale mining. These different-scale analyses were then integrated to create a record of 46 years of mining activity and land cover change in Tortiya. While similar in spatial extent, the mining/ bare class in the integrated analysis exhibits a substantially different spatial distribution than in the original classifications. This additional information regarding the locations of ASM activity in the Tortiya area is important from a policy and planning perspective. The results of this study also suggest that LULC classifications of Landsat imagery do not consistently capture areas of ASM in the Côte d'Ivoire landscape.

1. Introduction

Over the past several decades, a multitude of global and regional factors have shifted the land use and land cover (LULC) patterns surrounding Tortiya, Côte d'Ivoire from industrial-scale diamond mining to small-scale diamond mining to cashew tree farming. The political and economic effects of these changes have significant bearing on both current and future land use planning for the region, but currently no detailed geospatial record of LULC trends exists to inform these decisions and policies. Diamond mining and tree farming occur at vastly different geographic scales, but may compete for similar space in the Tortiya landscape. These competing land requirements of the mineral extraction and agribusiness sectors create the potential for renewed conflict in a country recently recovering from a civil war partially motivated by land tenure disputes. Remote sensing analysis methods provide independent quantification of land cover trends and are ideally suited for rural, data-scarce environments. However, the differing scales of LULC in Tortiya require the integration of different resolutions of data in order to quantify LULC trends back to the time of industrial mining.

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Côte d'Ivoire is a key exporter of agricultural commodities such as cocoa, coffee, pineapples, and palm oil. Although cashew trees were introduced to West Africa by Portuguese traders in the 1500s, this crop's expansive growth as a key agricultural export did not occur until the formation of the African Cashew Alliance, sponsored by the United States Agency for International Development (USAID) in 2005. Since that time, cashews have become a principle export, and Côte d'Ivoire has established itself as one of the world's leading cashew producers (Phipps, 2011, ACI, 2010, Foretell Business Solutions Private Limited, 2014). In recent years, large plantations of cashew trees have expanded across the country, particularly in the north where the climate is well-suited to cashew cultivation (ACI, 2010, Foretell Business Solutions Private Limited, 2014). Côte d'Ivoire's mineral sector includes industrial-scale and artisanal and small-scale (ASM) extraction of diamonds and other minerals. Both primary and secondary alluvial diamond deposits have been identified throughout the northern part of the country, including in the Tortiya region. In 1948 the Société Anonyme de Recherche et d'Exploitation Minières en Côte d'Ivoire (SAREMCI) mining corporation opened an industrial-scale diamond mine along the Bou River in the Katiola Prefecture, located in northern Côte d'Ivoire (Greenhalgh, 1985). The town of Tortiya was created by SAREMCI to house mine workers and provide associated services (Freudenberger, 2015). The Tortiya diamond mine operated for nearly 30 years and produced between 150,000 and 175,000 carats (cts) per year at its height until its abandonment in 1975 (Chirico and Malpeli, 2013). With the mine's closure, the town of Tortiya declined and conflict ensued between rival villages and former mine workers over ownership and usage of the abandoned mine land (Dejong, 2013; Freudenberger et al., 2015). Soon after its closure, people began to mine independently for diamonds within the industrial mine's boundaries. ASM entails the manual excavation of mine pits by individuals or groups of diggers using basic equipment and methods. In Tortiya, ASM miners search for diamonds, which occur in near-surface alluvial sediments and saprolite layers. ASM pits are typically small (1–5 m in diameter), and excavated piles of soil and gravel are placed in the surrounding de-vegetated area. Though no official census of ASM activity was conducted for Tortiya, estimates of the number of active artisanal miners diminished from around 40,000 in 1980 (UNGoE, 2011) to around 1000 in 2011 (Chirico and Malpeli, 2013).

In Côte d'Ivoire, civil war was sparked by issues of nationality and land tenure in the late 1990s, and the period of government instability and violence lasted through the early 2000s (Dejong, 2013; Chirico and Malpeli, 2013). Although international intervention quelled the initial violence, evidence that diamond profits had contributed to financing the rebellion resulted in an embargo on rough diamonds of Ivorian origin by the United Nations Security Council (UNSC) and the Kimberley Process (KP) in 2003. Despite the embargo, ASM activity continued across the country (UNGoE, 2011). Violence erupted again following presidential elections in 2010, but by 2014 efforts by Côte d'Ivoire's new government and international partners brought the country into compliance with KP regulations and legal diamond exports resumed.

Today, tensions over land tenure and usage in the Tortiya region are exacerbated by rapid LULC transitions from traditional subsistence agriculture to ASM and extensive cashew orchards. In these situations those with mining interests and community land rights have opposed the encroachment of cashew plantations, as well as the increased oversight and diamond certification requirements imposed by the Côte d'Ivoire government and the KP (Freudenberger et al., 2015). Conversely, those who have invested in the cashew industry are concerned that mining activity might expand into cashew orchards and disrupt production (Dejong, 2013).

Existing remote sensing studies of LULC change in Africa have focused on a multitude of wide-reaching transitions from natural to agricultural and urban land covers, generally as the result of population and economic pressures or changing climate (Muriithi, 2016; Dewan and Yamaguchi, 2009; Kusimi, 2008; Yiran et al., 2012; Wasige et al., 2013). Regional- and local-scale LULC changes are also of significant social and economic importance to community planning and conflict management endeavors, but may require more customized analysis techniques (Kibret et al., 2016; Marx, 2016). The temporal and spectral resolution of Landsat satellite imagery, along with its forty-two year archive (Landsat Missions, 2014) allows for analysis of decadal changes in regional-scale land cover patterns. Many studies have found the moderate spatial resolution of Landsat image pixels (30 m) to be useful in the automated classification of regional-scale LULC (Kibret et al., 2016; Muriithi, 2016). However this regional scale is potentially ill-suited to the mapping of fine-scale ASM activity and to detecting changes in other economically-significant but spatially-compact land uses (Kibret et al., 2016). Multiple studies have noted that the mapping of ASM locations using moderate-scale imagery, such as that from the Landsat or SPOT sensors, is difficult due to the small footprint of ASM and its spectral similarity with related land uses (Kusimi, 2008; Elmes et al., 2014).

One of the first efforts to map ASM over large areas integrated a variety of remote sensing methods, including automated classification of moderate resolution multispectral imagery, change detection of radar data, aerial photography, and field observation (Telmer and Stapper, 2007). The procedures adopted by that study resulted in general classification of ASM-related land uses, and included village areas and transportation corridors. Furthermore, the study relied heavily on the spectral contrast between ASM land use and undisturbed healthy vegetation (Telmer and Stapper, 2007). More recently, object-based image analysis (OBIA) methods have been investigated as a means of detecting the sedimentation of water-filled ASM pits and patterns of vegetation regrowth (Pagot et al., 2008), as well as a multi-scalar approach using 6.5 m and 0.5–1 m imagery to detect individual ASM features (Luethje et al., 2014) The latter method, though not field validated, also used a secondary textural analysis to differentiate between 'potential mining areas' from settlements. Sub-pixel classification methods, including spectral mixture analysis of Landsat imagery to detect sub-pixel changes in forest cover associated with ASM have also been investigated (Asner et al., 2013; Elmes et al., 2014). At the other end of the spatial scale, the hydrological and geomorphological changes caused by industrial-scale mining operations have been analyzed using moderate resolution imagery and also globally-available DEM data combined with high-resolution satellite imagery (Emel et al., 2014; Merriam et al., 2015). In each of these studies, large multi-pit ASM sites were successfully mapped, but potentially also included areas of mixed land use, such as settlements and transportation corridors. Moreover, much of the research on remotely sensed ASM mapping has focused on areas of relatively expansive ASM impact. Many of these studies report that small areas of ASM may have been omitted from the mapped areas. A second gap in the literature associated with remote sensing of ASM is the absence of a comprehensive, regional analysis of LULC changes associated with ASM. This study attempts to fill this gap by suggesting a method whereby regional LULC and ASM activity are quantified independently, then analyzed together to allow for comprehensive understanding of multi-scale landscape changes.

To address these gaps in the literature, this study examines how regional-scale and fine-scale analyses of remotely sensed data may be integrated to address long-term spatio-temporal trends in industrial-scale and artisanal and small-scale mining as well as competing (agricultural) land uses. The study merges support vector machine (SVM) image classification of moderate-scale multispectral data with data derived from manual interpretation and classification of VHR imagery using geographic information system (GIS) techniques. Although Côte d'Ivoire has a tropical environment, the northern area selected for this study does not contain the stark contrast between vegetation and soil contrast that has been present in other remote sensing studies of ASM. This woody savannah environment is typical of many areas of ASM in West and Central Africa, particularly during the dry season.