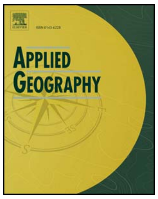
Applied Geography 89 (2017) 124–132

Contents lists available at ScienceDirect

Applied Geography

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



Spatio-temporal patterns of land use and cropping frequency in a tropical catchment of South India

F. Wilken[a,b], P.D. Wagner[c,b,*], B. Narasimhan[d,b], P. Fiener[a,b]

[a] Institut für Geographie, Universität Augsburg, D-86159 Augsburg, Germany
[b] Indo-German Centre of Sustainability, Indian Institute of Technology Madras, Chennai 600 036, India
[c] Department of Hydrology and Water Resources Management, Institute for Natural Resource Conservation, Kiel University, D-24118 Kiel, Germany
[d] Environment and Water Resource Engineering Division, Department of Civil Engineering, Indian Institute of Technology Madras, Chennai 600 036, India

ARTICLE INFO

Keywords:
Land use
Cropping frequency
Irrigation
Tropics
South India

ABSTRACT

India's rapid population and economic growth leads to fast changing land use and management practices that have a major impact on the environment. Therefore, this study assesses spatio-temporal dynamics of land use and cropping frequencies using moderate resolution spaceborne data (Landsat 7 and LISS III). Based on a hierarchical knowledge-based classification approach, multi-temporal satellite data from the years 2000/2001 and 2010/2011 have been used to derive land use and cropping frequency maps. The approach adopted in this study resulted in a satisfactory classification quality as indicated by overall accuracies > 90% for the individual classifications. A reduced land use pressure on mountainous areas was found, indicated by an increasing development of forests within the transition zones between cultivated land and steep slopes. Furthermore, an increase of tree plantations points to a shift from drought vulnerable plants to less risk prone perennial plants. We found a higher cropping frequency in 2010/11 related to both inter-annual precipitation differences over the course of the rainy season and long-term socio-economic changes. While low yield areas are left for natural succession or switched to tree plantations, the cultivation of high yield areas was intensified.

1. Introduction

Land use is one of the most important human impacts on global and regional water cycles (Foley et al., 2005). The importance of land use changes for water resources management is widely recognized (DeFries & Eshleman, 2004; Stonestrom, Scanlon, & Zhang, 2009) and is illustrated by the fact that irrigated agriculture accounts for about 90 percent of water withdrawal in the developing world (Cai & Rosegrant, 2002). To account for future food demands, adaption of water management (e.g. irrigation efficiency) and land management (e.g. changes of cropland intensity) are required (Malek & Verburg, 2017).

Countries with rapidly growing economies and population often face dynamic changes in land use and cropping intensity (Rao & Pant, 2001). However, the patterns of land use intensity in these countries are often poorly understood (Kuemmerle et al., 2013). India, as a prominent example, experiences both rapid urban expansion (e.g., Wagner, Kumar, & Schneider, 2013) and increasing vulnerability of smallholder farmers with regard to climate change and climate variability (Jain, Mondal, DeFries, Small, & Galford, 2013; Morton, 2007).

Moreover, India is confronted with a very pronounced, monsoon-driven rainfall that results in seasonal water scarcity, so that water management is one of India's environmental major issues (Cosgrove & Cosgrove, 2012; Seckler, Barker, & Amarasinghe, 1999). Further, an increasing food and the associated irrigation water demand will exacerbate the current situation in the future (De Fraiture et al., 2007). Therefore, adapted land management strategies need to be developed and evaluated. Such strategies typically aim at reducing the agricultural water consumption (e.g., by changing to less water intensive crops, or by increasing water use efficiency) or sustaining and enhancing the use of rainwater harvesting structures. The evaluation of these measures substantially relies on accurate information of current and past land use and management. Remote sensing provides suitable data to derive spatially explicit land use information (Coops & Waring, 2001) that can serve as input data for e.g. hydrologic models (DeFries & Eshleman, 2004). However, the derivation of the spatio-temporal patterns of land use and cropping frequency in India is complex due to the variability of rainfall, e.g. land use patterns depend on the spatial distribution of hydrologic variables (Wagner & Waske, 2016) and multiple cropping depends on the available irrigation water (Jain et al., 2013). Moreover, arable land is highly fragmented due to the

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[*] Corresponding author. Department of Hydrology and Water Resources Management, Institute for Natural Resource Conservation, Kiel University, Olshausenstr. 75, D-24118 Kiel, Germany.

E-mail address: pwagner@hydrology.uni-kiel.de (P.D. Wagner).

http://dx.doi.org/10.1016/j.apgeog.2017.10.011
Received 10 June 2016; Received in revised form 20 October 2017; Accepted 21 October 2017

smallholder based agro-economic structures (Heller et al., 2012; Jain et al., 2013). Remote sensing based land use change investigations in South India are often based on a visual interpretation of satellite images (e.g., Chauhan & Nayak, 2005; Dharumarajan et al., 2017; Fox et al., 2017; Jaiswal, Saxena, & Mukherjee, 1999; Jayakumar & Arockiasamy, 2003; Muthukumar, 2013) and single-date classification schemes (e.g., Adhikari, Southworth, & Nagendra, 2015; Shamsudheen, Dasog, & Tejaswini, 2005; Shetty, Nandagiri, Thokchom, & Rajesh, 2005). Moreover, a majority of studies focused on shifts between urban and forest land use (e.g., Rahman, Aggarwal, Netzband, & Fazal, 2011; Venkatesh, Lakshman, & Purandara, 2014), whereas detailed information especially on changes in cropping frequency are still rare.

Against this background, the objectives of this study are: (i) To map land use and cropping frequencies and (ii) to analyse the spatio-temporal patterns of land use and cropping frequencies over a decade in the meso-scale catchment of the Upper Pennaiyar in South India.

2. Materials and methods

2.1. Study area

The Upper Pennaiyar catchment (5335 km^2, Fig. 1) is located in the Indian states of Tamil Nadu, Karnataka, and (to a small extent) Andhra Pradesh (Fig. 1). The elevation ranges from 1470 m in the northwest to 400 m above m.s.l. in the south where the Krishnagiri reservoir is located. The topography of the north-western (upper) parts is slightly undulated. Further downstream, a linear mountain range separates the upper part of the catchment from the lower part. The mountain range is mainly characterized by exposed bedrock and steep slopes. In the lower parts, the relief is relatively flat but occasionally interrupted by isolated rock outcrops.

The climate is tropical, dominated by the seasonality of the southwest and northeast trade winds (summer and winter monsoon, respectively; Fiener, Gottfried, Sommer, & Steger, 2014) with rainfall occurring between June and December. In the pre-monsoon season (March–May) regularly occurring thunderstorms cause rainfall events (Bhowmik, Roy, & Kundu, 2008). Due to the influence of both monsoon and the pre-monsoon, two annual precipitation peaks can be found, in May as a result of the pre-monsoon and in September/October caused by the summer/winter monsoon. The annual precipitation at Bangalore (at the western border of the catchment) and Krishnagiri (at the southeastern outlet of the catchment) are in the same range (Krishnagiri annual mean: 924 mm, standard deviation: 270 mm, daily maximum: 170 mm; Bangalore annual mean: 1074 mm, standard deviation: 283 mm, daily maximum: 306 mm for the period from 1982 to 2011). Due to the low latitude, the annual temperature amplitude is rather low (21 °C–28°; based on mean monthly temperatures measured at Bangalore between 1982 and 2011).

Arable cropping is traditionally carried out in two periods that are associated with water availability. During the rainy season (June to December), the so called *Kharif* crops (Krishna & Morrison, 2010) are cultivated based on a combination of rain-fed and irrigated farming. Typical *Kharif* crops are finger millet, groundnut and pulses; whereas rice is planted as a cash crop in areas of substantial irrigation potential. Following the *Kharif* crops, the so called *Rabi* crops are cultivated (January to March). Crop types in the *Rabi* season are strongly dependent on the local availability of irrigation resources and typically have a high water use efficiency, e.g. drought resistant finger millet can either be cultivated rain fed or irrigated. Cultivation during the summer period is negligible (Indian Ministry of Agriculture, 2013) and solely possible along perennial streams. In general, the cropping frequency is strongly linked to water availability and hence, the highest land management intensities are found in proximity to water harvesting ponds, perennial streams and in areas of shallow groundwater resources (Krishna, 2010). Whereas cropland is mostly located in relatively flat terrain that is suitable for irrigation, semi-natural forest as well as shrubland and grassland are mainly found at steeper slopes. In the west, the megacity Bangalore is expanding into the catchment area (Fig. 1). For the evaluation of spatially distributed changes, the catchment was sub-divided into 26 sub-catchments.

2.2. Data

Overall, six cloud-free scenes of the Landsat 7 Enhanced Thematic Mapper (ETM+; 30 m × 30 m) sensor were analysed for the cultivation period of 2000/01. As the swath of an individual ETM+ scene does not cover the entire study area, two corresponding scenes for each time step are merged. Hence, three scenes for the western and three scenes for the eastern part of the catchment were used. For 2010/11 we used three cloud-free Resourcesat-1 Linear Imaging Self-scanning Sensor (LISS; 23.5 m × 23.5 m) III scenes (Indian Space Research Organization) that cover the entire catchment (Table 1). The sensors were chosen with respect to their similar spatial and spectral resolution. The spatial resolution of the LISS III was linearly resampled to match the resolution of the ETM+ sensor (30 m × 30 m). Scenes at the end of *Kharif* and during *Rabi* were selected, as cloud-free images were not available for the peak monsoon season. To derive the maximum extent of the pond surface area, representing the case of a very wet monsoon season, an additional scene from the Landsat 5 Thematic Mapper (TM) in the exceptionally wet year of 1992 was used. Pre-processing of the satellite data includes an atmospheric correction based on the Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes (FLAASH; Adler-Golden et al., 1999; Matthew et al., 2000, 2002) and a geometric correction based on measured reference points for those scenes that exhibit geometric errors larger than the size of one pixel. For topographical information, the 90 m × 90 m resolution digital elevation model of the Shuttle Radar Topography Mission (SRTM; Jarvis, Reuter, Nelson, & Guevara, 2008) was used and linearly resampled to match the ETM+ sensor resolution of 30 m × 30 m.

Three field surveys (Dec. 2011; Mar. 2012; May 2012) were conducted at ten test sites in the catchment area to map forest, shrub- and grassland, rocks, urban areas, ponds, tree plantations, palm trees, rice and other cropland. These areas were complemented with additional ground truth interpreted from Google Earth images (DigitalGlobe, CNES, Astrium; version 7.1.2.2041), summing up to a total area of approximately 1190 ha. For the cultivation period of 2000/01 ground truth was interpreted from those Google Earth images that were temporarily as close as possible to 2000/01. In addition, these data were checked for consistency with the satellite data to ensure that land use did not change. The ground truth data was split into two independent data sets, one used for training the classification algorithm and the other used for validating the classification results.

2.3. Land use and cropping frequency classification

The analysis of temporal changes in land use and in particular in cropping frequency (expressed as the number of crops cultivated per year) requires the use of multi-temporal satellite images which allow a regular intra-annual monitoring of land use and enable a comparison of different cultivation periods (Heller et al., 2012). Linking multi-temporal satellite images to additional sources of geo-information (e.g., digital elevation model (DEM), plant growth conditions) enhances the level of information, enables implementation of knowledge-based rules, and has demonstrated its abilities to improve land use and management analysis (e.g., Benediktsson & Sveinsson, 2003; Watanachaturaporn, Arora, & Varshney, 2008).

The classification is based on a stepwise determination of different land use and cropping frequencies within arable land. Therefore, we combined knowledge-based rules and geo-information (e.g. slope, irrigation potential) with single-date and multi-temporal satellite data. Overall, the following classes were distinguished: Forest, shrub- and grassland, rock, urban, ponds (with current water extent), tree