Int J Appl Earth Obs Geoinformation 72 (2018) 26–33

Contents lists available at ScienceDirect

Int J Appl Earth Obs Geoinformation

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

Designing a field sampling plan for landscape-pest ecological studies using VHR optical imagery

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ARTICLE INFO

Keywords:
Heliocheilus albipunctella
Millet
Senegal
Pest control
Pleiades images
Sampling design

ABSTRACT

The objective of this study was to develop an easily replicable sampling methodology using very high spatial resolution (VHSR) optical imagery to study the effect of landscape composition on crop pest incidence and biological control. The methodology was developed for the millet head miner (MHM), *Heliocheilus albipunctella* (de Joannis) (Lepidoptera: Noctuidae), a key pest of millet in Senegal (West Africa). The sampling plan was developed according to two main hypotheses: (i) pest incidence increases with millet abundance in the landscape, and (ii) biological control increases with the abundance of semi-natural habitats in the landscape. VHSR satellite imagery (< 1 m) provided from a *Pléiades* sensor was used to map and to quantify the landscape elements. Covering a square region of 20 × 20 km, a hierarchical, broad-scale land cover map focusing on crop (millet and peanut crops) and tree (tree vegetation) categories was produced and validated with ground truth data. Then, the landscape variables (tree density index and millet crop density index) were calculated based on a regular grid of 100 ha for each cell size covering the study area; the variables were then split into three density classes (low-medium-high) representative of the full landscape heterogeneity and combined into nine landscape patterns. Finally, according to sampling capacity, track accessibility, and statistical constraints, 45 field sites, including five replicates for each landscape pattern, were validated and selected for pest monitoring.

1. Introduction

The spatial distribution and dynamics of crop pest populations and their trophic interactions with primary resources and natural enemies often depend on ecological processes occurring at scales larger than the single crop plot (e.g., Kareiva and Wennergren, 1995; Ricklefs and Schluter, 1993; Tscharntke et al., 2007, 2005; Kareiva and Wennergren, 1995; Ricklefs and Schluter, 1993; Tscharntke et al., 2007, 2005). Landscape composition can affect pest abundance directly by hindering its dispersal, mortality or reproduction or indirectly by fostering its natural enemies. Many studies in recent years, as reviewed by Bianchi et al. (2006a); Chaplin-Kramer et al. (2011), and Veres et al. (2013), have shown that the landscape complexity and particularly higher proportions of semi-natural areas exhibited lower pest abundance or higher pest control in fields. It is therefore important to finely characterize landscape features to better understand how they can affect the spatial dynamics of crop pest populations and their natural enemies (Forman, 1995; Gustafson, 1998; Tischendorf and Fahrig, 2000; Turner et al., 2001). The calculation of landscape indices derived from thematic maps are generally used to quantify the landscape patterns and to test the relationships between landscape properties (composition and/or structure) and the distribution of insect populations (e.g., Forman, 1995; Gustafson, 1998; Tischendorf and Fahrig, 2000; Turner et al., 2001; Carrière et al., 2012). However, sampling strategies and underlying ecological assumptions are rarely well argued. A common statement in landscape-pest studies is that to be efficient, a sampling strategy must be based on environmental gradients that are believed to exercise primary control over the distribution of the crop pest populations and their natural enemies, and the sampling sites must be independently and identically distributed. In the majority of such studies, the environmental gradients are rarely fully considered over the entire study area, and the number of sites and their replicates are often limited because of technical and cost constraints (Veres et al., 2013). However, the proportion of the host-crop and non-crop habitat areas are mostly retained as explanatory landscape variables, and the technologies currently available based on earth observation data could help to fill these

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https://doi.org/10.1016/j.jag.2018.05.016
Received 20 December 2017; Received in revised form 29 May 2018; Accepted 29 May 2018
Available online 05 June 2018
0303-2434/

limitations. To identify arable fields from natural and semi-natural vegetation, remote sensing data are particularly useful since they provide a synoptic view and deliver information over large areas at a high level of detail (Nagendra, 2001). There is a large variety of sensors with a wide range of spatial and spectral resolutions. In landscape-pest studies, remote sensing imagery has rarely been used because the spatial resolution was insufficient to identify habitat biodiversity in highly fragmented areas and because the cost remained too high. However, available sensors with a sub-meter resolution (< 0.5 m) such as Quick bird or WorldView-2 sensors have shown promising results for natural vegetation identification and in particular for tree species at the crown scale (Cho et al., 2015; Immitzer et al., 2012; Karlson et al., 2014; Tooke et al., 2009). This development opens new perspectives in the ecological domain for the identification of species or groups of tree species that could promote crop pest natural regulation.

The aim of the paper is to study how very high spatial resolution (VHSR) optical imagery can help in performing a stratified sampling method that is easily replicable for landscape-pest studies and uses to pest biocontrol models. More specifically, the proposed sampling strategy aims to provide a representative data set including two main statistical constraints: to sample along a relevant gradient of the landscape patterns according to landscape-pest hypotheses, within a highly constrained framework in terms of the number of sampling sites; and to maximize the probability of observing the variability of pest incidence, natural regulation, and insect diversity, especially for natural enemies. In this way, the sampling plan would serve both for field data collection (pest, natural enemies, disease) and as a second step to calculate the pertinent landscape variables around each preselected sampling points that could be tested statistically in landscape pest models.

Therefore, the sampling methodology was developed from the millet head miner (MHM), *Heliocheilus albipunctella*, (de Joannis) (Lepidoptera: Noctuidae), as a case study. This insect species is a key pest of pearl millet in West Africa (Ajayi, 1980; Guevremont, 1982; Ndoye, 1979), causing yield losses up to 85% (Krall et al., 1995; Youm and Owusu, 1998). This study was carried out over an area in the Senegalese Peanut Basin where pest regulation relies only on the action of natural enemies, and the sampling plan was developed according to two main hypotheses that are often tested in landscape-pest studies: (i) pest incidence increases with millet abundance as the “host crop” in the landscape, and (ii) biological control increases with the abundance of semi-natural habitats in the landscape. Very high-resolution remote sensing data were chosen to map the landscape elements because of the small size of the objects that structure the landscape elements, focused on crops (millet and peanut crops) and trees (tree vegetation) as well as the heterogeneity of their spatial distribution. Then, we derived landscape variables to perform the sampling design.

2. Methods

2.1. Study area

The study was carry in the Bambey agroforestry parklands (14° 43′ 42″ N, 16° 33′ 98″ E) located in the Peanut Basin, which is the most important area for staple crop production in Senegal (Fig. 1). Covering an area of approximately 20×20 km, this study site was selected because of the spatial heterogeneity of semi-natural vegetation patterns (Fig. 1) and the absence of any insecticidal treatments, which could disturb the biological control of the MHM by natural enemies. Characterized by a semi-arid climate with only one short rainy season from July to October and average annual rainfall varying from 400 up to 600 mm (Badiane et al., 2000), the landscape is characterized by a mosaic of arable land under *Faidherbia albida* parklands. The agricultural system is based on smallholder farming (approximately 0.25 ha) of staple crops dominated by millet and nuts covering 52% and 32%, respectively, of the Bambey area in 2014 (DAPSA, 2014). Livestock farmers and growers live together on the same space.

The *F. albida* parkland is primarily composed of centuries-old trees that are mostly isolated and regularly distributed. To a lesser extent, other tree species are presents in the study area, including *Guiera senegalensis*, *Balanites aegyptica*, *Adansonia digitata, Tamarindus indica* and *Acacia seyal*. The spatial distribution of the trees is characterized by a high spatial heterogeneity, with the highest densities in the North-West and the South-East of the study area.

2.2. Environmental data

A *Pléiades* satellite image was acquired on January 16th, 2013, at a ground resolution of 0.5×0.5 m in the panchromatic mode and 2×2 m in the multispectral mode, with blue (B), green (G), red (R) and near infrared (NIR) bands. The acquisition date was chosen during the middle of the dry season when most tree crowns were leafy and crops had just been harvested. At this time, millet and peanut fields are characterized by the presence of crop residue and bare soil, respectively. In February 2013, a land-cover field survey was conducted in the study area (Fig. 1). The monitored sites were previously selected using a stratified equal sampling procedure based on a previously acquired *Pléiades* image. Therefore, using the ArcGIS software, the study area was split into 9 tiles, and the sandy tracks were manually drawn. To facilitate the field navigation, we chose sampling sites along the sandy tracks. Twenty sampling sites per image tile, focusing on trees and crops, were preselected via image interpretation of the *Pléiades* scene, and the sites were integrated into a GIS database. Then, the sampling points were exported into a GPS (global positioning system) device, allowing easy navigation of each sampling point. In the field, the vegetation information was collected on the preselected focus point but also within their vicinity, with the aim to collect as much information as possible regarding the vegetation type. The vegetation, including crops and trees, was described on a total of 420 sites with approximately 50 sampling sites per image tile. All this information was geolocalized using a GPS and integrated into a geographic information system (GIS) database.

2.3. Image processing for land cover mapping

A common pre-processing procedure was applied to the *Pléiades* satellite image, including orthorectification and conversion of digital numbers to the top of the atmospheric reflectance. Then, we chose an object-oriented approach and defined a mapping processing chain including different levels of segmentations at various scales and a hierarchical classification (Blaschke, 2010). While it is essential to capture small landscape elements, since the image resolution was smaller than or similar in size to the objects of interest (namely, trees and small patches of land), there was a large variability of intra-class spectral signatures and other per-pixel indicators (Blaschke et al., 2014). Thus, pixel-based classifications would lead to a speckled result far from a mapping product. In addition, strong post-processing smoothing would also decrease the potential accuracy of the classification. For the calibration of the method and learning the algorithms, we split the initial 420-sites of the ground truth data set, leaving 164 sites for the evaluation step and addressing only the 256 sites remaining. A radiometric and textural analysis was then performed on these 256 learning sites to identify the most relevant descriptors of the land covers, with a special focus on major crops (millet and peanut) and the most abundant tree species. First, 36 potentially explicative radiometric variables proposed in the eCognition Developer® software (Baatz and Schäpe, 2000) were derived, including, for example, the normalized difference vegetation index (NDVI) and the normalized difference water index (NDWI), which are useful to discriminate vegetation from bare soil and to separate different classes of vegetation (Pettorelli et al., 2005; Tucker, 1979). The soil-adjusted vegetation index (SAVI, Huete (1988)) and the brightness index are known to minimize the influences of the soil brightness from the spectral vegetation (Pouget et al., 1990). Then, 64