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Large-scale monitoring of coppice forest clearcuts by multitemporal very high resolution satellite imagery. A case study from central Italy

Gherardo Chirici [a,*], Diego Giuliarelli [b], Daniele Biscontini [c], Daniela Tonti [a], Walter Mattioli [b], Marco Marchetti [a], Piermaria Corona [b]

[a] ECOGEOFOR — Laboratorio di Ecologia e Geomatica Forestale, Dipartimento di Scienze e Tecnologie per l'Ambiente e il Territorio, University of Molise, Contrada Fonte Lappone, I-86090 Isernia, Pesche, Italy

[b] DISAFRI — Dipartimento di Scienze per l'Ambiente Forestale e delle sue Risorse, University of Tuscia, Via San Camillo de' Lellis, I-01100, Viterbo, Italy

[c] E-Geos spa, Roma, Italy

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A B S T R A C T

Reliable assessment of forest resource stock, productivity and harvesting is a commonly agreed objective of environmental monitoring programs. Distinctively, the assessment of wood harvesting has become even more relevant to evaluate the sustainability of forest management and to quantify forest carbon budget. This paper presents the development and testing of procedures for assessing forest harvesting in coppice forests by very high resolution (VHR) satellite imagery. The study area is located in central Italy over approximately 34,000 km^2. A set of SPOT5 HRG multispectral images was acquired for the study years (2002–2007). Official administrative statistics of coppice clearcuts were also acquired. More than 9500 clearcuts were mapped and dated by on-screen interpretation of the SPOT5 images. In a subset of the study area various methods for semi-automatic clearcut mapping were tested by pixel- and object-oriented approaches. The following results are presented: (*i*) clearcut map developed by visual interpretation of the SPOT5 images resulted in high thematic (overall accuracy of 0.99) and geometric (root mean square error of clearcut boundary delineation of 5.3 m) reliability; (*ii*) object-oriented approach achieved significantly better accuracy than pixel-based methods for semi-automatic classification of the coppice clearcuts; (*iii*) comparison between mapped clearcut area and official forest harvesting statistics proved a significant underestimation by the latter (65% of the total mapped clearcut area). A sample-based procedure exploiting VHR satellite imagery is finally proposed to correct the official statistics of coppice clearcuts.

1. Introduction

Reliable assessment of forest resource stock, productivity and harvesting is a commonly agreed objective of environmental monitoring programs at various spatial scales (Köhl et al., 2006; Corona & Marchetti, 2007; McRoberts & Tomppo, 2007). Distinctively, the assessment of wood harvesting has become even more relevant to check the sustainability of forest management and to quantify forest carbon budget. For instance, the countries are asked to report this information within the framework of Forest Europe (the former Ministerial Convention on the Protection of Forests in Europe) (MCPFE, 2009), in the Montréal Process (2005), in the framework of the United Nations Framework Convention on Climate Change (UNFCCC, 2007) and the Kyoto Protocol (1997) and for the Global Forest Resource Assessment carried out by the Food and Agriculture Organization of the United Nations (FAO, 2005).

The forest area in Italy is 87,592 km^2 (29% of the total land area), 42% of which is managed as coppice forest (INFC, 2007). The majority are coppices with standards, that is even-aged stands with 40–200 trees of two to three times the rotation age released at the coppicing time (Ciancio et al., 2006). Felling is carried out by clearcutting at the end of rotation (usually 15–35 years), on areas from few square hundred meters up to 10–20 ha (but most clearcuts are usually in the range 1–3 ha). Coppice is the only silvicultural system for which clearcut is allowed in Italy, with a harvesting season from November to March or April. The main product is fuelwood, and, at much less extent, polewood. In the last years the increased oil prices and the increased concern for energy renewable sources have increased fuelwood demand, for both domestic and industrial uses (Lasserre et al., 2010). Current stumpage prices are around 20–40 euros per ton, on average.

In most Italian Regions (European Union NUT2 administrative units) a simple forest owner declaration communicated to the Regional authority and to the Italian State Forest Service (Corpo Forestale dello Stato — CFS) is usually enough to start the harvesting of a coppice stand, at least for clearcut areas smaller than 3 ha. For wider clearcut areas a specific project approved by the competent

* Corresponding author. Tel.: +39 0874404138; fax: +39 0874404123.
E-mail addresses: gherardo.chirici@unimol.it (G. Chirici), daniele.biscontini@telespazio.it (D. Biscontini), piermaria.corona@unitus.it (P. Corona).

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Regional authority is needed. Thus, it is possible that forest owners tend to declare clearcut areas smaller than 3 ha even if the cut is carried out on a wider area. An accurate assessment of clearcut areas is missing because only few of the declarations on clearcuts by forest owners are checked in the field. The information declared by forest owners and the information from the harvesting projects are recorded by the State Forest Service and aggregated by the National Statistics Agency (Istituto Nazionale di Statistica - ISTAT) for national and international reporting purposes.

Several authors have criticized this procedure for the likely underestimation of the resulting harvested fuelwood statistics (e.g., Cutolo, 2000; Corona et al., 2004). Hence it was urgent in Italy to empirically evaluate whether more objective methods for forest clearcut assessment could be adopted to derive more reliable statistics of annual forest clearcut area. National Forest Inventories report clearcut area and other forest harvesting statistics, but in Italy (and in most of the other countries where NFIs are carried out routinely) this information is not available on a yearly figure. In this condition remote sensing is potentially recognized as a suitable and cost-effective tool.

The potential of remote sensing-based monitoring of forest disturbances, including harvesting, has been explored by many authors, mainly relying on change detection techniques (e.g., Coppin & Bauer, 1996; Coppin et al., 2004; Lu et al., 2004). As concerns forest definition, national and international reporting processes are generally based on a minimum mapping unit of 0.5 ha (Vidal et al., 2008): remotely sensed images with very high geometric resolution (VHR) are thus preferred. Airborne VHR imagery is less effective in terms of the ratio of quality to cost than satellite images for the multitemporal monitoring and assessment of forest resources over large areas. Available satellite VHR images are represented e.g. by Formosat, IKONOS, QuickBird, OrbView-3, SPOT5 HRG, WorldView-2, Pleiades.

On the other hand, most commonly applied satellite imagery reported in literature with respect to harvesting monitoring is Landsat (TM or ETM+). Some application can be found even as concerns low resolution data such as MODIS, NOAA-AVHRR, and SPOT Vegetation. Multisensor approaches are also exploited, combining the information content of cross-sensor imagery (Wulder et al., 2004), or combining satellite imagery with orthophotos (Saksa et al., 2003), or with radar imagery (Thiel et al., 2006).

Satellite monitoring of forest harvesting are reported for tropics (e.g., Souza et al., 2005; Hayes & Sader, 2001), USA (e.g., Schroeder et al., 2007; Jin & Sader, 2005; Cohen et al., 1998; Healey et al., 2006; Sader et al., 2003; Wilson & Sader, 2002; Bertrand et al., 2000), Canada (e.g., Franklin et al., 2000; Wulder et al., 2007), boreal Europe (e.g., Olsson, 1994; Hame, 1991; Heikkonen & Varjo, 2004; Saksa et al., 2003).

At least to our knowledge, no studies have been devoted to satellite monitoring of coppice stand harvesting (most probably, results concerning this topic are not published nor are they accessible), although coppice is a silvicultural system widespread over Mediterranean countries, covering more than 20 million hectares in the Mediterranean Europe (Ciancio et al., 2006) and becoming even more important in the perspective of biomass production for energy uses (Lasserre et al., 2010).

According to Desclée et al. (2006), the techniques to monitor forest harvesting, and distinctively the clearcuts, by remotely sensed imagery can be classified into three main approaches: manual on-screen interpretation and delineation, pixel-oriented classification, object-oriented classification.

The first approach is based on visual interpretation of multitemporal imagery and on-screen delineation in a GIS environment (Watrin & Rocha, 1992). The quality of obtained products is dependent to some degree on interpreter subjectivity. Automatic (unsupervised) and semi-automatic (supervised) methods of forest disturbances detection have been developed to produce cheaper and more objective products. Conventional approaches are pixel-based and can be implemented by postclassification change differencing (delta classification), or by classification of raw multitemporal dataset, or creating artificial images by combining the original spectral bands of several multitemporal images by image differencing, principal component analysis, tasseled cap transformation, multitemporal RGB composite: reviews of these methods for monitoring forest disturbances are reported e.g. by Muchoney and Haack (1994); Coppin and Bauer (1996) and Hayes and Sader (2001).

More recently, object-oriented methods (Wulder et al., 2004) proved to be valuable for semi-automatically miming the texture contextual analysis typical of the visual interpretation with the objective and replicable approach of pixel-based classification (Desclée et al., 2006; Lamonaca et al., 2006).

Considering that no experiences have been published about satellite monitoring of Mediterranean coppice clearcuts, the following questions were addressed in this study: (*i*) is it possible to map and date clearcut in coppice forest by visual interpretation of multitemporal SPOT5 images? (*ii*) what is the accuracy of the resulting maps? (*iii*) is it possible to semi-automate the mapping of coppice clearcuts on the basis of pixel-oriented or object-oriented classification methods? (*iv*) is it feasible the exploitation of the clearcut map from SPOT5 imagery to correct official statistics?

To answer these questions a test area of 34,000 km^2 was surveyed in central Italy (Fig. 1) within the framework of the project GMES (Global Monitoring for Environment and Security) Service Element Forest Monitoring. The area was covered by multitemporal SPOT5 HRG images (Fig. 2) that, after pre-elaboration, were visually interpreted in order to derive a map of coppice clearcuts (paragraph 4.1). The map was independently validated to quantify its thematic and geometric accuracy. The official harvesting statistics were acquired for the same area and for the same years, and compared with the clearcut area mapped (paragraph 4.3). In a subsample of the study area, pixel-oriented and objected-oriented classification approaches to semi-automatically detect clearcuts were applied and their accuracy contrasted (paragraph 4.2). Results are presented and discussed in Section 5 and conclusions are drawn in Section 6.

2. Study area

The study area is located in central Italy, over 34,000 km^2 mainly within the Mediterranean biogeographical zone, from seaside up to the Appennine mountains (Fig. 1).

In this area coppice forests are dominated by oaks, with prevailing Turkey oak (*Quercus cerris*) and downy oak (*Quercus pubescens*), and are characterized by rotation ages usually between 18 and 25 years, with most clearcuts usually 1–2 ha wide.

3. Imagery and ancillary information

The study area is fully covered by 10 SPOT5 frames and 3 SPOT5 stripes (Fig. 2). For this study, 22 multitemporal SPOT5 images were acquired in the years 2003–2007, mainly in spring and early summer.

SPOT5 images were geometrically orthocorrected with parametrically derived polynomial transformation equations based on Ground Control Points (GCPs) acquired on high resolution digital orthphotos or topographic maps and on the basis of a 75 m resolution digital elevation model. The resulting average positional accuracy of orthocorrected SPOT5 images, expressed as root mean square error (RMSE), was lower than one pixel (10 m). The resulting images were projected in the UTM33N system with datum WGS84.

The normalized difference vegetation index (NDVI) was calculated for each image. Additional available information was: digital elevation model (DEM) with a spatial resolution of 75 m; black and white aerial digital orthophotos for the years 2002–2007, having a geometric resolution of 1 m; a raster forest/non-forest mask for all the study area with 25 m resolution, developed by the Joint Research Centre of the European Commission (Pekkarinen et al., 2009). For a subset of the