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Continued loss of temperate old-growth forests in the Romanian Carpathians despite an increasing protected area network

THEMATIC SECTION
Biodiversity Governance in Central and Eastern Europe

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SUMMARY

Old-growth forests around the world are vanishing rapidly and have been lost almost completely from the European temperate forest region. Poor management practices, often triggered by socioeconomic and institutional change, are the main causes of loss. Recent trends in old-growth forest cover in Romania, where some of the last remaining tracts of these forests within Europe are located, are revealed by satellite image analysis. Forest cover declined by 1.3 % from 2000 to 2010. Romania's protected area network has been expanded substantially since the country's accession to the European Union in 2007, and most of the remaining old-growth forests now are located within protected areas. Surprisingly though, 72% of the old-growth forest disturbances are found within protected areas, highlighting the threats still facing these forests. It appears that logging in old-growth forests is, at least in part, related to institutional reforms, insufficient protection and ownership changes since the collapse of communism in 1989. The majority of harvesting activities in old-growth forest areas are in accordance with the law. Without improvements to their governance, the future of Romania's old-growth forests and the important ecosystem services they provide remains uncertain.

Keywords: biodiversity governance, Central and Eastern Europe, deforestation, disturbance, forest restitution, Landsat, Natura 2000, old-growth forests, protected areas, remote sensing

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INTRODUCTION

Across the globe biodiversity is declining and the '2010 target' of the Convention on Biological Diversity (CBD) has not been met (CBD 2010). The destruction and fragmentation of habitat along with overexploitation are the main causes of the global biodiversity crisis (MA [Millennium Assessment] 2005; Brook *et al.* 2008; Ehrlich & Pringle 2008). Old-growth forests play a key role in maintaining biodiversity and are irreplaceable for sustaining biodiversity (Gibson *et al.* 2011). Moreover, old-growth forests play an important part in the response to climate change. Contrary to the long standing view that they are carbon neutral, they continue to sequester carbon for long time periods, but also store more carbon per unit area than any other ecosystem or forest successional stage (Luyssaert *et al.* 2008; Knohl *et al.* 2009; Wirth 2009; Keeton *et al.* 2011), though future sequestration dynamics under altered climate remain uncertain. Old-growth forests in the Carpathian Mountain region of Europe, in particular, store very high levels of carbon in comparison to younger and managed forests (Holeksa *et al.* 2009; Keeton *et al.* 2010).

Despite their ecological importance, old-growth forests around the globe are vanishing at an alarming rate mainly due to deforestation, unsustainable logging practices, and increases in fire frequency (Achard *et al.* 2009). Ecosystem services they provide (such as genetic resources, protection from natural hazards and riparian functionality) are thereby diminished (Keeton *et al.* 2007; Wirth *et al.* 2009*a*) and biodiversity they harbour is threatened. In the industrialized countries of northern Europe especially, land-use changes and conversion of primary forests to managed plantations have almost completely eradicated old-growth forests (Wirth *et al.* 2009*b*). Of the total forest area in central Europe, only 0.2% of old-growth forests have survived, mainly in remote, mountainous areas or within nature reserves (Frank *et al.* 2009; Schulze *et al.* 2009).

Goods and services from European temperate forests, such as clean water, wood products and recreation opportunities in relation to the large number of people living in close proximity, make these forests socioeconomically important (Thompson *et al.* 2009). One area where forests are particularly valuable in this respect is the Romanian Carpathians, comprising the eastern and southern extension of the mountain range. Here, vast forests including large tracts of old-growth forests, provide important habitat for the largest European populations of brown bear *(Ursus arctos)*, gray wolf *(Canis lupus)*, and lynx *(Lynx lynx)*. Moreover, these old-growth forests have been recognized for their exceptional biodiversity harbouring many endemic, rare and threatened species (Biriş & Veen 2005; Ioras & Abrudan 2006; Biriş *et al.* 2010).

While using the term 'old-growth forests', we follow Wirth *et al.* (2009*b*) and Burrascano (2010) in including widely accepted criteria for moist temperate old-growth forests: relatively old stand age, abundance of large old tree species, deadwood components (both standing and downed), dominance by late-successional tree species, vertically complex canopies and horizontal structural heterogeneity (namely gap mosaics). These elements of stand structural complexity correlate with a variety of habitat functions for late-successional forests; these are frequently missing or under-represented in younger or managed forests (Keeton 2006; Smith *et al.* 2008).

Assessing the status of old-growth forests in the Carpathians is difficult due to often outdated, incomplete and fragmented forest resource information. The last official national forest inventory for Romania was carried out in 1984 (Brandlmaier & Hirschberger 2005; Marin *et al.* 2010). Nevertheless, a comprehensive scientific assessment of the status of old-growth forests was performed in Romania between 2001 and 2004 (Veen *et al.* 2010), identifying approximately 210 000 ha of old-growth forest, comprising 3.5% of total Romanian forest cover. This is more than in any other Central European country. However, the extent of Romania's old-growth forest has decreased substantially from approximately 2 million ha at the end of the 19th century to 700 000 ha in 1945 and 400 000 ha in 1984 (Veen *et al.* 2010). Severe threats for these forests include illegal logging, invasive species and climate change (Biriş & Veen 2005; Price *et al.* 2011).

Following the collapse of communism in 1989, the next two decades in Central and Eastern Europe (CEE) were characterized by a weakening of civil societies and a decline in political participation (Howard 2003). Especially in Romania, biodiversity governance remained challenging due to weak collaboration between the environmental sector and state administration (Börzel & Buzogány 2010). Protecting biodiversity often competes with forestry, constrains other land uses, and may foster conflicts with livelihoods (Niedziałkowski *et al.* 2012). Thus, a key challenge for CEE countries remains the goal of increasing public involvement in biodiversity governance (Niedziałkowski *et al.* 2012).

In this context, one of the most pressing recent threats in Romania relates to the changes in forest ownership pattern (Nijnik *et al.* 2009; Griffiths *et al.* 2012; Knorn *et al.* 2012). Large areas of state forest have been restituted to prior owners, and often this has resulted in forest management changes (MCPFE [Ministerial Conference on the Protection of Forests in Europe] 2007; Barbier *et al.* 2010; Lambin & Meyfroidt 2010). Economic hardship accompanied by weak political institutions encouraged land owners receiving restituted forests to liquidate their timber assets through harvesting (Turnock 2002; Nichiforel & Schanz 2011). The combination of an uncertain institutional environment (Lambin *et al.* 2001), poverty and the high timber value of old-growth forests additionally increased exploitation beyond sustainable levels (Anfodillo *et al.* 2008). Moreover, the fast growing number of small-scale forest holdings (approximately 800 000 by the end of the restitution process) (Ioras & Abrudan 2006) has hampered the establishment of sustainable forest management practices and hindered biodiversity governance (Turner *et al.* 1996; Nijnik *et al.* 2009; Żmihorski *et al.* 2010). Lastly, weak law enforcement fosters logging practices and magnitudes outside legal norms (Brandlmaier & Hirschberger 2005; Knorn *et al.* 2012). These continuing threats and losses reinforce the need for an up-to-date estimate of old-growth forest disturbances in Romania and further analysis of protected area governance aimed at safeguarding these forests.

Satellite image interpretation is the most accurate and comprehensive approach for assessing forest cover changes across large areas (Achard *et al.* 2009; FAO [Food and Agriculture Organization of the United Nations] 2011). Images from the Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) sensors are able to capture canopy removal reliably across large regions (Young *et al.* 2006; Fraser *et al.* 2009; Huang *et al.* 2009), including for parts of the Carpathians (Mihai *et al.* 2007; Kozak *et al.* 2008; Kuemmerle *et al.* 2009; Main-Knorn *et al.* 2009). Satellite analyses are particularly well suited to map forest disturbances because the reflectance of a given pixel apparently changes when the structure of a forest canopy is significantly impacted, either due to harvesting or due to natural disturbance (Coppin *et al.* 2004). In contrast, it is much harder to distinguish old-growth forests from other forests, because the spectral difference between the two is subtle (Wulder 1998). Consequently, mapping old-growth disturbances based on satellite imagery is feasible only in areas where an accurate map of old-growth forest distribution already exists.

Our goal here was to quantify disturbance (defined in our case as full canopy removal due to either natural disturbances, such as wind or insects, or anthropogenic disturbances, such as logging) in Romanian old-growth forests, based on the delineations from the last assessment in 2004. We recognize that low to moderate intensity wind disturbances and other natural mortality events result only in partial canopy disturbance, with abundant residual live and dead

Table 1 Potential natural vegetation of the Carpathian chain based on data from Donita *et al.* (1993, 2005), Cristea (1993), Muica and Popova-Cucu (1993) and Feurdean *et al.* (2007). Numbers in squared brackets refer to the Southern Carpathians, otherwise to the Northern Carpathians.

Vegetation belt	*Sub layer*	*Altitude (m)*	*Main vegetation*
Deciduous forest belt	I. Pure sessile oak and mixed sessile oak-european beech	300 [400]–500 [650]	*Quercus petraea, Fagus sylvatica,*
	II. Pure beech and mixed beech with silver fir and/or Norway spruce	500 [650]–1300 [1450]	*Fagus sylvatica, Abies alba, Picea abies*
Spruce forest belt	I. Mountainous norway spruce	1300 [1450]–1600 [1700]	*Picea abies*
	II. Pre-subalpine Norway spruce	1600 [1700]–1750 [1850]	*Picea abies*
Sub-alpine belt		1750 [1850]–2000 [2200]	*Pinus mungo, Juniperus communis* ssp. *nana*
Alpine belt		>2000 [2200]	Dwarf shrubs, short-grass meadows

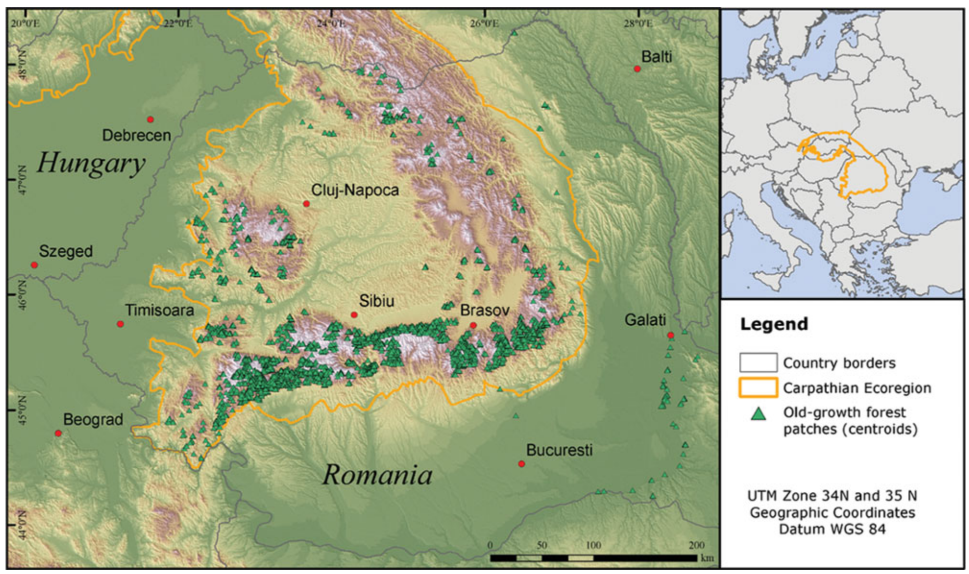

Figure 1 Study area in the Carpathian Mountains in Romania including the distribution of old-growth forest patches (Source: SRTM digital elevation model, see URL http://srtm.csi.cgiar.org; ESRI Data and Maps Kit, see URL http://www.esri.com/data/data-maps).

trees (Splechtna *et al.* 2005; Nagel *et al.* 2006). In primary systems, and where salvage logging does not occur, these biological legacies are incorporated into recovering forests, often producing multi-aged stands containing remnant old-growth elements (Franklin *et al.* 2000; Keeton *et al.* 2010). However, for the purpose of our study, we were most concerned with the combined effects of deliberate forest clearing by people and high-intensity (sometimes termed 'catastrophic') natural disturbances. Specifically, we asked the following research questions: (1) To what extent did disturbances occur in Romanian old-growth forests between 2000 and 2010? (2) How were disturbances distributed among vegetation zones, and along gradients in elevation and slope? (3) How effective have protected areas been in safeguarding old-growth forests in Romania?

METHODS

Study area

The Carpathians are Europe's largest mountain range, encompassing the continent's largest continuous temperate forest ecosystem (UNEP [United Nations Environment Programme] 2007). Approximately half of the Carpathian forests are located in Romania. Our study area comprised all of the Romanian Carpathian forests (Fig. 1). In the study region, elevation (height above sea level) ranges from 0 m to >2500 m and the climate is transitional temperate-continental. The natural vegetation of the Carpathian chain generally occurs within altitudinal layers (Donita *et al.* 1993, 2005) (Table 1).

The 2001–2004 old-growth forest assessment (Veen *et al.* 2010) identified 3402 sites of old-growth forest larger than 50 ha. These old-growth forests were located mainly in montane areas (92% above 600 m) and predominately within the Carpathian Ecoregion (Fig. 1) (Anfodillo *et al.* 2008; Veen *et al.* 2010). European beech as the dominant old-growth forest type (58%), followed by coniferous forests, including Norway spruce, silver fir, Swiss stone pine *(Pinus cembra)* European larch *(Larix decidua)* and Scots pine *(Pinus sylvestris)* (dwarf pine habitats were not included in the assessment) (Biriş & Veen 2005; Veen *et al.* 2010).

Datasets used

We used digital maps of areas of old-growth forests (polygon layer) in Romania recorded between 2001 and 2004 (Biriş & Veen 2005) as our baseline, provided by the Romanian Forest Research and Management Institute (ICAS).

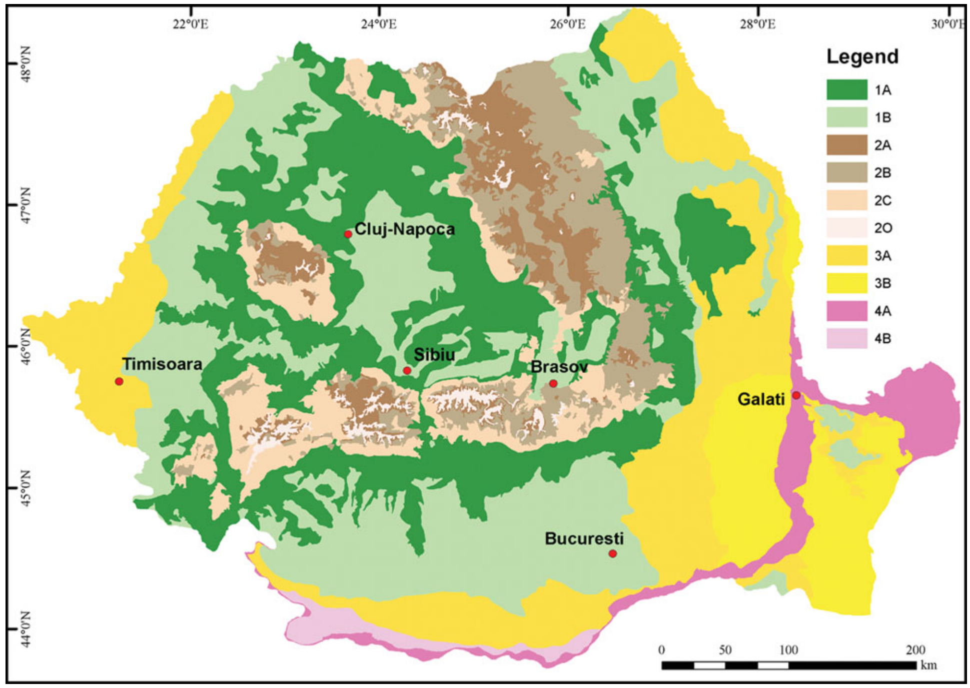

Figure 2 Map of Romania's forest-ecozones. 1A = beech and sessile oak mixed forests, Hungarian oak *(Quercus frainetto)* and mixtures, on high and medium hills; 1B = forests with pedunculate oak *(Quercus robur)*, Turkey oak *(Quercus cerris)*, Hungarian oak and other species, on low hills and plains; 2A = spruce forests; 2B = coniferous and beech mixed forests; 2C = beech mountainous forests; 2O = alpine grasslands and/or bare rocks; 3A = xerophyte oak forests in silvosteppe; 3B = steppe (no natural forest vegetation); 4A = floodplain forests with poplar *(populus)*, willow *(Salix)*, alder *(Alnus)* and some pedunculate oak; and 4B = high floodplain forests with pedunculate oak and ash *(Fraxinus excelsior)*.

Forest cover changes from 2000 to 2010 were mapped across Romania using Landsat TM/ETM+ images including SLC-off imagery (thermal bands were not incorporated) for 16 footprints with a spatial resolution of either 28.5 or 30 m. Whereas most of the images had already been orthorectified by the United States Geological Survey (Level 1T), several uncorrected images (Level 1G) needed to be co-registered to the others. To do so, 1500 tie points were located using an automated point matching tool (Leica Geosystems 2006) considering both the acquisition geometry and relief (Griffiths *et al.* 2012). Results showed an overall positional error below 0.5 pixels.

Additional spatial data included administrative boundaries (ESRI Data and Maps Kit 2008, see URL http://www.esri.com/data/data-maps), protected area boundaries including Natura 2000 sites (digital datat supplied by ICAS), forest ecozones (digital data supplied by ICAS) (Fig. 2) and an enhanced digital elevation model (DEM) based on the Shuttle Topography Mission (SRTM, see URL http://srtm.csi.cgiar.org) resampled from 90 to 30 m. Forest-ecozones delineate Romania's major forest ecosystem regions (Fig. 2), and these were assessed from existing maps and ancillary data provided by ICAS, derived using guidelines provided by the Joint Research Center (JRC) (Gancz & Pătrăşcoiu 2000).

We conducted extensive field visits in northern, central-eastern and south-western Romania, and interviews with park administrations, stakeholders, non-governmental organizations, and several scientists and other partners during 2008, 2009 and 2010.

Forest disturbance mapping

Forest disturbance maps were obtained from three previous studies with foci on different regions in Romania. The first study (Griffiths *et al.* 2012) focused on central-eastern Romania (Landsat footprint path/row 183/028) and assessed forest disturbances on an annual basis between 1984 and 2010. The second study (Knorn *et al.* 2012) analysed forest disturbances in northern Romania (path/row 185/27) between 1987 and 2010. The third study (Olofsson *et al.* 2011) assessed forest disturbances between 1990 and 2010 for all of Romania. Based on those maps, we assembled a single map representing forest disturbances from 2000–2010 for all of Romania. Incorporating each of the studies was necessary since the map by Olofsson *et al.* (2011) partly missed data due to cloud coverage. All three maps were generated using either Support Vector Machines (Pal & Mather 2005), the Disturbance Index (Healey *et al.* 2005), the LandTrendr (Landsat-based detection of trends in disturbance and recovery) set of change detection algorithms (Kennedy *et al.* 2010) and/or Chain Classification (Knorn *et al.* 2009). Detailed descriptions of the specific approaches are found in the original studies of Griffiths *et al.* (2012), Olofsson *et al.* (2011) and Knorn *et al.* (2012). The original forest disturbance maps were subject to individual rigorous accuracy assessments, based on independent ground reference points. Reported overall accuracies of 86.5% (Olofsson *et al.* 2011), 94.9% (Knorn *et al.* 2012) and 95.7% (Griffiths *et al.* 2012) provided proof of the reliability of each map. To build a single area-wide forest disturbance map covering all of Romania's old-growth forests, maps from the three original studies were aggregated and the original classes merged to 'permanent forest', 'permanent non-forest' and 'forest disturbance' from 2000 to 2010. While assembling, the maps from Knorn *et al.* (2012) and Griffiths *et al.* (2012) were prioritized due to higher accuracies and temporal resolution. Finally, a minimum mapping unit of *c.* 0.4 ha

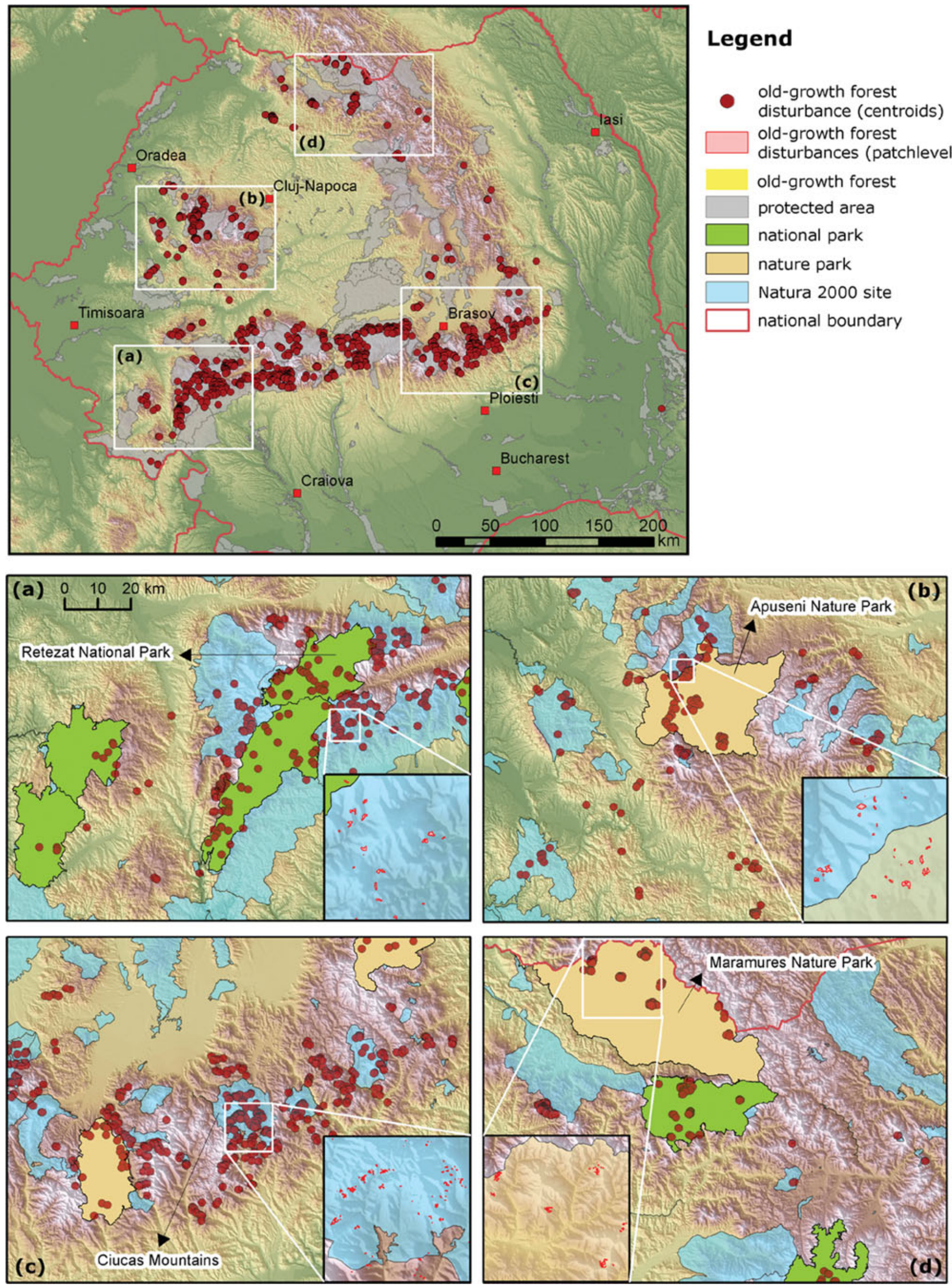

Figure 3 Distribution of old-growth forest disturbance patches in Romania. White squares highlight specific areas: (*a*) the South-Western Carpathians, (*b*) the Apunseni Mountains, (*c*) the Curvature Carpathians, and (*d*) the Maramures and Rodna Mountains.

(4 pixels) was applied on the compiled map (Knorn *et al.* 2012).

Comparison of old-growth forest disturbances

Using the area-wide forest disturbance map, we summarized old-growth forest disturbances based on the polygons from the digital baseline map. We derived proportions of old-growth forest disturbances in relation to both forest ecozones and protected areas. For the protected area comparison, we first assessed the total amount of old-growth forest area and old-growth forest disturbances within protected areas independent of the protection status. Second, we differentiated disturbance rates by protected area type (whether Natura 2000, National Park or Nature Park). In Romania, National Parks are in IUCN category II whereas Nature Parks are in IUCN category V. However, there is a significant overlap between Natura 2000 sites and other protected areas (Fig. 3) (Ioja *et al.* 2010). In the study area, *c.* 85% of National/Nature Park areas were also Natura 2000 sites, making the protection status of Natura 2000 sites variable. Natura 2000 sites (terrestrial area) covered 42 650 km^2 (17.89% of Romania) and National/Nature Parks covered 10 800 km^2 (4.5%). We also assessed the distribution of old-growth forest disturbances with respect to altitude and slope by categorizing the DEM into 100-m wide elevation classes and eight slope classes each 5° wide.

In addition to the situation inside old-growth forest patches, the degree of fragmentation of the surrounding forest matrix is also important. Discontinuities and contrast in patch edges enhance the vulnerability of tall old forests to natural disturbances, alter propagule dispersal, and facilitate movement of invasive species and domesticated fauna (Foster *et al.* 1996). To determine the intactness of the surrounding landscape, we summarized the area of forest disturbances within 250 m of each old-growth forest patch. The total area of these buffer zones was equal to the total area of the old-growth forest in the baseline map (*c.* 210 000 ha).

RESULTS

In total, 1.3% (2720 ha) of old-growth forest was disturbed during the last decade, taking into account that 7238 ha (*c.* 3.4%) of the inventoried 210 882 ha old-growth forest stratum could not be classified owing to clouds or cloud shadows in the satellite imagery. Old-growth forest disturbances were mainly concentrated along the interior mountain complexes of the Carpathian Ecoregion (Fig. 3). Clusters of disturbance occurred in the Maramures Mountains in the north, the Apuseni Mountains in the west and the south/south-western rim of the Carpathian mountain chain (Fig. 3).

The old-growth forest disturbance map revealed considerable differences in the distribution of disturbance among forest ecozones (Fig. 4*a*). Disturbances were most prevalent in the forest ecozone 'beech mountainous forests' (850.2 ha), followed by 'coniferous and beech mixed forests' (726.2 ha) and 'spruce forests' (457.7 ha). Fractions of disturbances among forest ecozones were similar to the respective fractions of the original old-growth forest area. However, coniferous forests generally exhibited higher disturbance rates and deciduous forests lower disturbance rates than the respective distribution of old-growth forests would have let expect (Fig. 4*a*).

The highest amount of old-growth forest disturbances was found at altitudes between 1200 and 1600 m, whereas their occurrence sharply decreased above 1600 m and gently towards hilly and plain areas below 800 m (Fig. 4*b*). Fractions of disturbances among altitude were broadly similar to the respective fractions of the original old-growth forest area (Fig. 4*b*). Old-growth forest disturbances occurred most frequently at slope gradients of between 15 and 25°, whereas just over 6% of all disturbances were found at slopes steeper than 35° (Fig. 4*c*).

Approximately 77% of the old-growth forest area was embedded within the Romanian protected area network. This included National Parks (23%; 37 917 ha old-growth forests), Nature Parks (14%; 22 435 ha old-growth forests), and Natura 2000 sites (63%; 161 565 ha old-growth forests, exclusive National/Nature parks) (Fig. 4d). In total, 72% of all disturbances in old-growth forests were found within a protected area. Of these, 8.5% (167 ha) were in National Parks, 22.1% (432 ha) in Nature Parks and 69.4% (1359 ha) in Natura 2000 sites (exclusive National/Nature parks) (Fig. 4*d*). Therefore, National Parks effectively prevent logging within old-growth forests.

Disturbances which occurred within a 250-m buffer from the old-growth forest patches sum up to 3290 ha. This corresponded to *c.* 1.6% of the entire area within 250 m and is thus 0.3% higher than the respective disturbed area within the original old-growth forests area.

DISCUSSION

Our remote sensing survey of old-growth forest stands in Romania revealed that disturbances in these stands occurred across the country, but were especially clustered in some areas, for example, in the Apuseni Mountains, the Maramures Mountains, the Curvature Carpathians and the South-Western Carpathians (Fig. 3). Disturbances seem triggered by high-value timber in old-growth stands, institutional changes in the Romanian forest sector and new ownership structures. Moreover, as cuttings in old-growth forests are predominantly in accordance with forest management plans, legal harvesting activities are obviously responsible for their diminishment. Protected areas, including recent expansions under the Natura 2000 framework, do not safeguard these forests as originally envisioned. Finally, disturbances in the matrix of forest communities surrounding old-growth forest patches additionally affect these old-growth forests negatively (Foster *et al.* 1996). Biodiversity and specifically protected area governance continue to face serious challenges with respect to their ability to safeguard old-growth forests.

Distribution of old-growth forest disturbances

Most old-growth forest stands and related disturbances were found in mountainous regions dominated by beech forests (Fig. 2 and 3, zones 1A, 2B and 2C), followed by spruce forests (zone 2A). Only very small fractions (0.92%) of disturbances occurred in the foothills or plains (zone 1B), including the Danube flood plain (Fig. 2 and 3, zone 4A), partly because these are areas where few old-growth forests remain. Approximately 50% of all disturbances occurred at altitudes between 1100 and 1500 m (Fig. 4*b*). Nevertheless, as disturbance fractions correspond to the distribution of the remaining old-growth forest portions, there were only minor deviations in the distribution of disturbances among forest ecozones (slightly more in the coniferous ecozones), altitude (slightly more between 1200 and 1600 m), or slope (slightly more on slopes with less than 25°). It is conspicuous though that more than 6% of all old-growth forests disturbances were found on slopes >35°. These forests are protected by law for flood and soil protection (Veen *et al.* 2010).

Natural versus anthropogenic disturbances

Natural stand-replacing forest disturbances, including insect infestation, windthrow, avalanches and sporadic fires, do

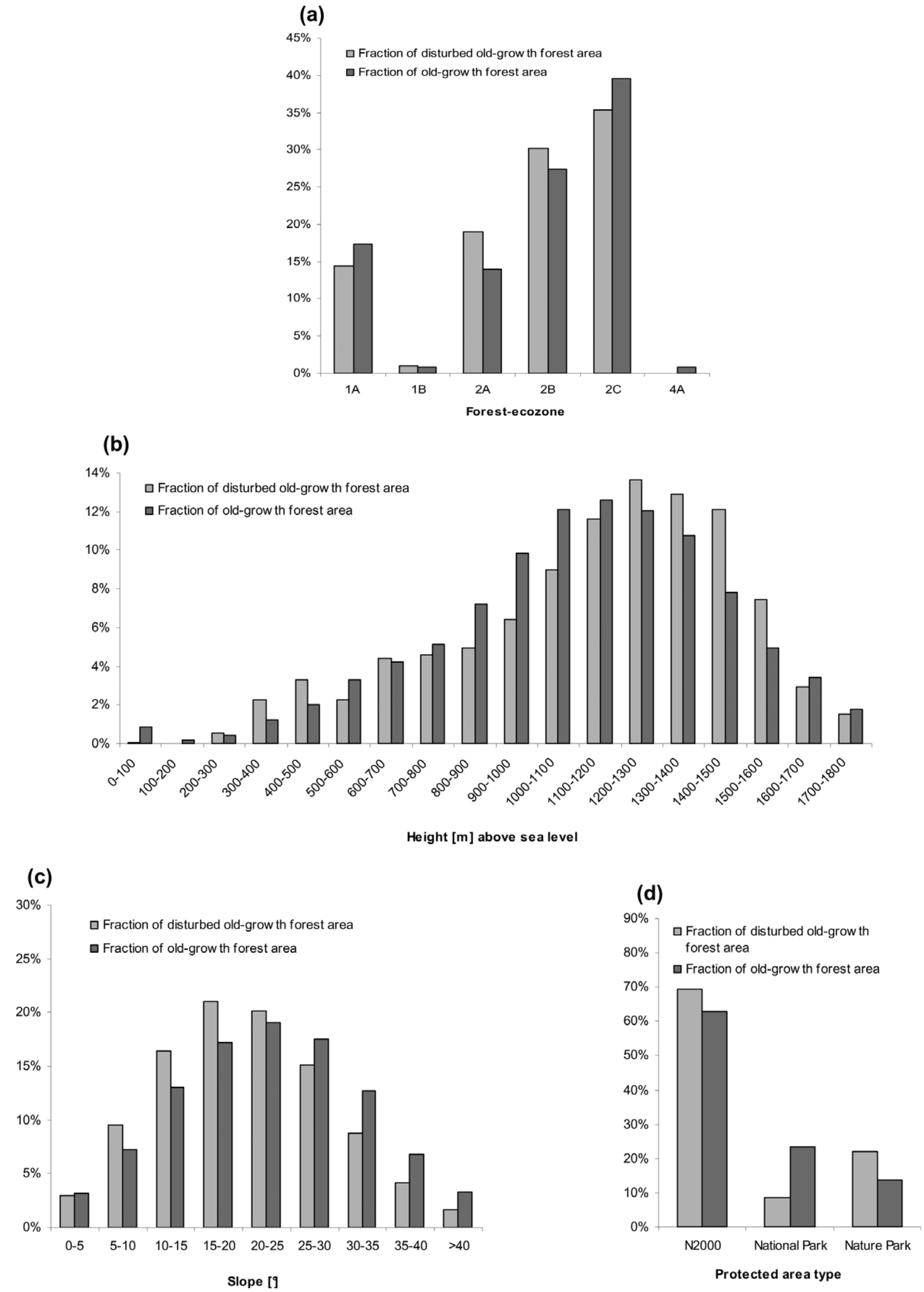

Figure 4 Fractions of old-growth forest disturbances and original old-growth forest area in relation to: (*a*) forest ecozones (abbreviations for forest-ecozone types are described in Fig. 2), (*b*) altitude, (*c*) slope, and (*d*) protected area type (N2000 = Natura 2000 site).

occur in the Romanian Carpathians (Schelhaas *et al.* 2003; Toader & Dumitru 2005). However, most of these disturbance types are either rare or only affect very small areas (i.e. smaller than our minimum mapping unit). Forest fires, for example, are not widespread in the Romanian Carpathians and are a negligible cause of disturbances (Anfodillo *et al.* 2008; Rozylowicz *et al.* 2011). Windthrow events are both relatively frequent and can cause severe disturbances. Nevertheless, Savulescu and Mihai (2011) suggested that wind disturbances in Romania mainly affected forests with features different from their natural or primary structure. Thus, old-growth forests are more resistant to larger wind impacts. Moreover, climate data suggest that windthrow events in general have a declining frequency for Romania since 1975 (Popa 2008). In other words, large-scale natural disturbances are often related to forest management or the legacies from past management (Schelhaas *et al.* 2003; Mollicone *et al.* 2006; Schulze *et al.* 2009). In the Carpathians, for example, spruce plantations often consist of genetically non-native spruce variants (Keeton & Crow 2009; Kuemmerle *et al.* 2009; Macovei 2009) that are more susceptible to disease and pests. Although impacts of windstorms on old-growth Norway spruce in the region have also been documented (Panayotov *et al.* 2011; Svoboda *et al.* 2012), the area affected remained relatively small. Old-growth spruce forests account only for 15% of our total old-growth forest area. Taken together, natural disturbances are therefore unlikely to explain the majority of forest cover changes in the old-growth stands that we observed.

Underlying causes of anthropogenic disturbances

We suggest that major socioeconomic transformations resulted in considerable economic hardship that, combined with the restitution process and insufficient protected area enforcement, may have resulted in logging of old-growth stands. Moreover, most logging activities are in accordance with forest management plans. Although we caution that a causal connection cannot be established based on our analyses alone, our results, expert interviews, our own previous studies (Griffiths *et al.* 2012; Knorn *et al.* 2012) and extensive field visits all suggest that the observed disturbances are closely related to the forest restitution process (Irimie & Essmann 2009; Mantescu & Vasile 2009). Widespread clear-cutting was witnessed after the first restitution law in 1991 (Nichiforel & Schanz 2011). Most of the restituted forests (approximately 300 000 ha) were cleared in the following years by new owners (Mantescu & Vasile 2009). Similar trends occurred in the subsequent restitution phases following the respective laws in 2000 and 2005 (Ioras & Abrudan 2006). When the restitution process will be finalized, about two-thirds (50% by 2011, according to the Romanian Ministry of Environment and Forests) of Romania's forests will be in private ownership (Ioras & Abrudan 2006). Doubts about the permanence of the newly gained property rights, lack of knowledge regarding sustainable forest management and nature conservation principles (UNDP [United Nations Development Programme] 2004), as well as the chance to gain short-term profits during times of economic hardship all possibly catalyse the harvesting of restituted forests (Nichiforel 2010; Nichiforel & Schanz 2011). Moreover, institutional adjustments necessary to cope with the new ownership structure lag far behind the actual rate of restitution (Irimie & Essmann 2009).

Furthermore, lack of transparency, corruption, and inadequate legal proceedings likely resulted in illegal harvesting activities (Brandlmaier & Hirschberger 2005). Harvested timber volumes were higher than official statistics indicate (Bouriaud 2005) and estimates of wood volume and quality were incorrect (Brandlmaier & Hirschberger 2005). Economic hardship was identified as the main driver of unauthorized logging in the region, as illegal logging was highly correlated with unemployment in rural areas (Bouriaud 2005). Moreover, the intensity of illegal logging and over-harvesting has been found to be higher in private forests compared to state forests (Bouriaud 2005). Last but not least, lack of resources and limited staffing within protected areas (Knorn *et al.* 2012) and in forest districts may hamper law enforcement of illegal harvesting in protected forests.

Protected area governance and old-growth forests

Nearly 80% of the remaining old-growth forests in Romania are found in protected areas, but 72% of the disturbances happened within their boundaries (Fig. 4*d*). Moreover, disturbance only differed slightly when comparing rates in protected (1.20%) versus unprotected (1.59%) old-growth forests. Only National Parks effectively prevented disturbances in old-growth forest (Fig. 4*d*).

Several reasons for the apparent shortcomings in protected area governance can be postulated. Although Romania has substantially increased its network of protected areas (Ioja *et al.* 2010), many still appear to be 'protected on paper' only (Börzel & Buzogány 2010). Although the establishment of the Natura 2000 areas was seen as an opportunity to direct biodiversity governance towards more inclusive policy-making, serious capacity problems undermined this idea (Börzel & Buzogány 2010). To date, owing to inappropriate administrations, the effective enforcement and implementation of conservation goals in Natura 2000 areas remains unachieved (Ioja *et al.* 2010). Moreover, wood harvesting in old-growth forests is strictly prohibited only inside the core zones of protected areas. Old-growth forests located outside these core areas, but inside buffer areas or completely outside protected areas, are exposed to legal harvesting conducted in accordance with forest management plans. The same applies for old-growth forests included in the Natura 2000 network, where the protection regime allows active forest management. According to forest management plans, by 2004 > 13 000 ha of old-growth forests had been included in the functional group of 'productive forests'. This implies that some forest removal had been foreseen; with few exceptions, harvesting in old-growth forests in Romania is therefore in accordance with the law. The only true safeguard from potential harvesting for many remaining old-growth forest patches is their inaccessibility due to the lack of necessary infrastructure.

CONCLUSIONS

Our study highlights that intact old-growth forest landscapes continue to disappear in the temperate zone. In Romania, more than 2720 ha of old-growth forests were lost from 2000 to 2010 (1.3% of the total old-growth forest cover). Although our remote sensing approach could not distinguish between natural and anthropogenic disturbances, extensive field visits, interviews with foresters and local experts, and our own previous studies (Griffiths *et al.* 2012; Knorn *et al.* 2012), suggest that natural disturbances alone cannot explain this loss. To the contrary, the observed decline in old-growth forest cover seems to result largely from logging.

Romania's protected area governance has not been successful in safeguarding these forests, confirming recent concerns about the effectiveness of nature protection in this region (UNEP 2007; Knorn *et al.* 2012). Therefore, a continued monitoring of old-growth stands is necessary, and, as shown in this analysis, satellite image interpretation offers a promising and valuable tool for doing so. Besides strengthening protected area governance, equally important is the protection of old-growth forests against legal cutting, potentially necessitating changes to current forest management plans. We recommend that old-growth forests be incorporated into core protected areas (for example IUCN category Ia), given that aims and principles of protected areas are rated more highly than the guidelines and regulations of forest management plans. Alternatively, a direct protection through forestry technical provisions stipulated in forest management planning should also be considered.

In a more general context, local institutions should be established to promote the vertical and horizontal participation of multiple stakeholders to address the underlying social and economic challenges. In doing so, a sustaining multifunctional forest management and protected area governance may emerge, incorporating biodiversity, sustainable production, livelihoods and cultural heritage (Nijnik 2004; Bizikova *et al.* 2011). Additionally, incentives for private forest owners may encourage them to manage their forests sustainably and compensate them for the loss of opportunities, for example in the case of old-growth forests (Brandlmaier & Hirschberger 2005; Dragoi 2010). Similarly, forest carbon management should be taken into account in biodiversity governance, as it offers alternative financial benefits (Olofsson *et al.* 2011; FAO 2012). Furthermore, government interventions may be justified for biodiversity governance because forestry in countries that are going through the transition from communism to market-economics is often characterized by weak institutions and profit seeking (Nijnik 2004). Finally, capacity–building and social learning (Schneider & Ingram 1990) would be extremely valuable, including the raising of public awareness (Biriş & Veen 2005) with respect to the exceptional biodiversity and value of the ecosystem goods and services that Romania's old-growth forests provide.

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References

Achard, F., Eva, H., Mollicone, D., Popatov, P., Stibig, H.-J., Turubanova, S. & Yaroshenko, A. (2009) Detecting intact forests from space: hot spots of loss, deforestation and the UNFCCC. In: *Old-Growth Forests*, ed. C. Wirth, G. Gleixner & M. Heimann, pp. 411–427. Berlin and Heidelberg, Germany: Springer.

Anfodillo, T., Carrer, M., Valle, E.D., Giacoma, E., Lamedica, S. & Pettenella, D. (2008) Report on current state of forest resources in the Carpathians. INTERREG III B CADSES Programme Carpathian Project, Dipartimento Territorio e Sistemi Agro-Forestali, Università Degli Studi Di Padova, Legnaro, Italy.

Barbier, E.B., Burgess, J.C. & Grainger, A. (2010) The forest transition: towards a more comprehensive theoretical framework. *Land Use Policy* **27**(2): 98–107.

Biriş, I.-A. & Veen, P. (2005) Inventory and strategy for sustainable management and protection of virgin forests in Romania. Extended English summary (PIN-MATRA / 2001 / 018). ICAS and KNNV, Bucharest, Romania: 61 pp.

Biriş, I.A., Doniţă, N. & Teodosiu, M. (2010) Forêt vierges en Roumanie. *Braun-Blanquetia* **46**: 139–144.

Bizikova, L., Nijnik, M. & Kluvanková-Oravská, T. (2011) Sustaining multifunctional forestry through the developing of social capital and promoting participation: a case of multiethnic mountain communities. *Small-Scale Forestry*: 1–19.

Börzel, T. & Buzogány, A. (2010) Environmental organisations and the Europeanisation of public policy in Central and Eastern Europe: the case of biodiversity governance. *Environmental Politics* **19**(5): 708–735.

Bouriaud, L. (2005) Causes of illegal logging in Central and Eastern Europe. *Small-Scale Forestry* **4**(3): 269–291.

Brandlmaier, H. & Hirschberger, P. (2005) Illegal logging in Romania. Report. WWF European Forest Programme and the Danube Carpathian Programme (DCP): 17 pp. [www document]. URL http://assets.panda.org/downloads/finalromaniaillegallogging.pdf

Brook, B.W., Sodhi, N.S. & Bradshaw, C.J.A. (2008) Synergies among extinction drivers under global change. *Trends in Ecology and Evolution* **23**(8): 453–460.

Burrascano, S. (2010) On the terms used to refer to 'natural' forests: a response to Veen *et al*. *Biodiversity and Conservation* **19**(11): 3301–3305.

CBD (2010) *Global Biodiversity Outlook 3*. Montréal, Canada: Secretariat of the Convention on Biological Diversity: 94 pp.

Coppin, P., Jonckheere, I., Nackaerts, K., Muys, B. & Lambin, E. (2004) Digital change detection methods in ecosystem monitoring: a review. *International Journal of Remote Sensing* **25**(9): 1565–1596.

Cristea, V. (1993) *Fitosociologie si vegetatia Romaniei*. Cluj Napoca, Romania.: Babes-Bolyai University Press.

Donita, N., Ivan, D., Coldea, G., Sanda, V., Popescu, A., Chifu, T., Paucă-Comănescu, M., Mititelu, D. & Boşcaiu, N. (1993) Vegetation potentielle de la Roumanie. *Braun-Blanquetia* **9**: 79.

Donita, N., Popescu, A., Paucă-Comănescu, M., Mihăilescu, S. & Biriş, I.A. (2005) *Habitatele din România*. Bucureşti, Romania: Editura Tehnică Silvică.

Dragoi, M. (2010) Compensating the opportunity cost of forest functional zoning: two alternative options for the Romanian forest policy. *Annals of Forest Research* **53**(1): 81–92.

Ehrlich, P.R. & Pringle, R.M. (2008) Where does biodiversity go from here? A grim business-as-usual forecast and a hopeful portfolio of partial solutions. *Proceedings of the National Academy of Sciences USA* **105**(Suppl. 1): 11579–11586.

FAO (2011) Global forest land-use change from 1990 to 2005. Initial results from a global remote sensing survey. Report, Food and Agriculture Organization of the United Nations, Rome, Italy.

FAO (2012) Forest management and climate change: a literature review. Working Paper Series, Food and Agriculture Organization of the United Nations, Rome, Italy.

Feurdean, A., Wohlfarth, B., Björkman, L., Tantau, I., Bennike, O., Willis, K.J., Farcas, S. & Robertson, A.M. (2007) The influence of refugial population on Lateglacial and early Holocene vegetational changes in Romania. *Review of Palaeobotany and Palynology* **145**(3–4): 305–320.

Foster, D.R., Orwlg, D.A. & McLachlan, J.S. (1996) Ecological and conservation insights from reconstructive studies of temperate old-growth forests. *Trends in Ecology and Evolution* **11**(10): 419–424.

Frank, D., Finckh, M. & Wirth, C. (2009) Impacts of land use on habitat functions of old-growth forests and their biodiversity. In: *Old-Growth Forests*, ed. C. Wirth, G. Gleixner & M. Heimann, pp. 429–450. Berlin and Heidelberg, Germany: Springer.

Franklin, J.F., Lindenmayer, D., MacMahon, J.A., McKee, A., Magnuson, J., Perry, D.A., Waide, R. & Foster, D. (2000) Threads of continuity. *Conservation in Practice* **1**(1): 8–17.

Fraser, R.H., Olthof, I. & Pouliot, D. (2009) Monitoring land cover change and ecological integrity in Canada's national parks. *Remote Sensing of Environment* **113**(7): 1397–1409.

Gancz, V. & Pătrăşcoiu, N. (2000) Cartografierea ecosistemelor forestiere din România prin mijloace GIS şi de teledetecţie. *Revista Pădurilor* **2**: 35–40.

Gibson, L., Lee, T.M., Koh, L.P., Brook, B.W., Gardner, T.A., Barlow, J., Peres, C.A., Bradshaw, C.J.A., Laurance, W.F., Lovejoy, T.E. & Sodhi, N.S. (2011) Primary forests are irreplaceable for sustaining tropical biodiversity. *Nature* **478**(7369): 378–381.

Griffiths, P., Kuemmerle, T., Kennedy, R.E., Abrudan, I.V., Knorn, J. & Hostert, P. (2012) Using annual time-series of Landsat images to assess the effects of forest restitution in post-socialist Romania. *Remote Sensing of Environment* **118**(0): 199–214.

Healey, S.P., Cohen, W.B., Yang, Z.Q. & Krankina, O.N. (2005) Comparison of Tasseled Cap-based Landsat data structures for use in forest disturbance detection. *Remote Sensing of Environment* **97**(3): 301–310.

Holeksa, J., Saniga, M., Szwagrzyk, J., Czerniak, M., Staszynska, K. & Kapusta, P. (2009) A giant tree stand in the West Carpathians. An exception or a relic of formerly widespread mountain European forests? *Forest Ecology and Management* **257**(7): 1577–1585.

Howard, M.M. (2003) *The Weakness of Civil Society in Post-communist Europe*. Cambridge, UK: Cambridge University Press.

Huang, C., Goward, S.N., Schleeweis, K., Thomas, N., Masek, J.G. & Zhu, Z. (2009) Dynamics of national forests assessed using the Landsat record: case studies in eastern United States. *Remote Sensing of Environment* **113**(7): 1430–1442.

Ioja, C.I., Patroescu, M., Rozylowicz, L., Popescu, V.D., Verghelet, M., Zotta, M.I. & Felciuc, M. (2010) The efficacy of Romania's protected areas network in conserving biodiversity. *Biological Conservation* **143**(11): 2468–2476.

Ioras, F. & Abrudan, I.V. (2006) The Romanian forestry sector: privatisation facts. *International Forestry Review* **8**(3): 361–367.

Irimie, D.L. & Essmann, H.F. (2009) Forest property rights in the frame of public policies and societal change. *Forest Policy and Economics* **11**(2): 95–101.

Keeton, W.S. (2006) Managing for late-successional/old-growth characteristics in northern hardwood-conifer forests. *Forest Ecology and Management* **235**(1–3): 129–142.

Keeton, W.S. & Crow, S.M. (2009) Sustainable forest management alternatives for the Carpathian Mountain region: providing a broad array of ecosystem services. In: *Ecological Economics and Sustainable Forest Management: Developing a Trans-disciplinary Approach for the Carpathian Mountains.*, ed. I. Soloviy & W.S. Keeton, pp. 109–126. Lviv, Ukraine: Ukrainian National Forestry University Press.

Keeton, W.S., Chernyavskyy, M., Gratzer, G., Main-Knorn, M., Shpylchak, M. & Bihun, Y. (2010) Structural characteristics and aboveground biomass of old-growth spruce–fir stands in the eastern Carpathian mountains, Ukraine. *Plant Biosystems. An International Journal Dealing with all Aspects of Plant Biology* **144**(1): 148–159.

Keeton, W.S., Kraft, C.E. & Warren, D.R. (2007) Mature and old-growth riparian forests: structure, dynamics, and effects on Adirondack stream habitats. *Ecological Applications* **17**(3): 852–868.

Keeton, W.S., Whitman, A.A., McGee, G.C. & Goodale, C.L. (2011) Late-successional biomass development in northern hardwood-conifer forests of the northeastern United States. *Forest Science* **57**(6): 489–505.

Kennedy, R.E., Yang, Z. & Cohen, W.B. (2010) Detecting trends in forest disturbance and recovery using yearly Landsat time series: 1. LandTrendr. Temporal segmentation algorithms. *Remote Sensing of Environment* **114**(12): 2897–2910.

Knohl, A., Schulze, E.-D. & Wirth, C. (2009) Biosphere–atmosphere exchange of old-growth forests: processes and pattern. In: *Old-Growth Forests*, ed. C. Wirth, G. Gleixner & M. Heimann, pp. 141–158. Berlin and Heidelberg, Germany: Springer.

Knorn, J., Kuemmerle, T., Radeloff, V.C., Szabo, A., Mindrescu, M., Keeton, W.S., Abrudan, I., Griffiths, P., Gancz, V. & Hostert, P. (2012) Forest restitution and protected area effectiveness in post-socialist Romania. *Biological Conservation* **146**(1): 204–212.

Knorn, J., Rabe, A., Radeloff, V.C., Kuemmerle, T., Kozak, J. & Hostert, P. (2009) Land cover mapping of large areas using chain classification of neighboring Landsat satellite images. *Remote Sensing of Environment* **113**(5): 957–964.

Kozak, J., Estreguil, C. & Ostapowicz, K. (2008) European forest cover mapping with high resolution satellite data: the Carpathians case study. *International Journal of Applied Earth Observation and Geoinformation* **10**(1): 44–55.

Kuemmerle, T., Chaskovskyy, O., Knorn, J., Radeloff, V.C., Kruhlov, I., Keeton, W.S. & Hostert, P. (2009) Forest cover change and illegal logging in the Ukrainian Carpathians in the transition period from 1988 to 2007. *Remote Sensing of Environment* **113**(6): 1194–1207.

Lambin, E.F. & Meyfroidt, P. (2010) Land use transitions: socio-ecological feedback versus socio-economic change. *Land Use Policy* **27**(2): 108–118.

Lambin, E.F., Turner, B.L., Geist, H.J., Agbola, S.B., Angelsen, A., Bruce, J.W., Coomes, O.T., Dirzo, R., Fischer, G., Folke, C., George, P.S., Homewood, K., Imbernon, J., Leemans, R., Li, X. B., Moran, E.F., Mortimore, M., Ramakrishnan, P.S., Richards, J.F., Skanes, H., Steffen, W., Stone, G.D., Svedin, U., Veldkamp, T.A., Vogel, C. & Xu, J.C. (2001) The causes of land-use and land-cover change: moving beyond the myths. *Global Environmental Change-Human and Policy Dimensions* **11**(4): 261–269.

Luyssaert, S., Schulze, E.D., Borner, A., Knohl, A., Hessenmoller, D., Law, B.E., Ciais, P. & Grace, J. (2008) Old-growth forests as global carbon sinks. *Nature* **455**(7210): 213–215.

MA (2005) *Ecosystems and Human Well-being: Biodiversity Synthesis*. Washington DC, USA: Island Press: 86 pp.

Macovei, C. (2009) The wind as a climatic risk factor for the forestry fund of Suceava county. *Present Environment and Sustainable Development* **3**: 275–286

Main-Knorn, M., Hostert, P., Kozak, J. & Kuemmerle, T. (2009) How pollution legacies and land use histories shape post-communist forest cover trends in the Western Carpathians. *Forest Ecology and Management* **258**(2): 60–70.

Mantescu, L. & Vasile, M. (2009) Property reforms in rural Romania and community-based forests. *Sociologie Românească* **VII**(2): 95–113.

Marin, G., Bouriaud, O., Marius, D. & Nitu, D. (2010) Romania. In: *National Forest Inventories. Pathways for Common Reporting*, ed. E. Tomppo, T. Gschwanter, M. Lawrence & R.E. McRoberts, pp. 473–480. Heidelberg, Germany: Springer.

MCPFE (2007) State of Europe's Forests 2007. The MCPFE Report on Sustainable Forest Management in Europe. Warsaw Ministerial Conference on the Protection of Forests in Europe and UNECE/FAO [www document]. URL http://www.foresteurope.org/filestore/foresteurope/Publications/pdf/state_of_europes_forests_2007.pdf

Mihai, B., Savulescu, I. & Sandric, I. (2007) Change detection analysis (1986–2002) of vegetation cover in Romania. A study of alpine, subalpine, and forest landscapes in the Iezer Mountains, Southern Carpathians. *Mountain Research and Development* **27**(3): 250–258.

Mollicone, D., Eva, H.D. & Achard, F. (2006) Ecology: human role in Russian wild fires. *Nature* **440**(7083): 436–437.

Muica, E.C. & Popova-Cucu, A. (1993) The composition and conservation of Romania's plant cover. *GeoJournal* **29**(1): 9–18.

Nagel, T.A., Svoboda, M. & Diaci, J. (2006) Regeneration patterns after intermediate wind disturbance in an old-growth Fagus-Abies forest in southeastern Slovenia. *Forest Ecology and Management* **226**(1–3): 268–278.

Nichiforel, L. (2010) Forest owners' attitudes towards the implementationof multi-functional forest management principles in the district of Suceava, Romania. *Annals of Forest Research* **53**(1): 71–80.

Nichiforel, L. & Schanz, H. (2011) Property rights distribution and entrepreneurial rent-seeking in Romanian forestry: a perspective of private forest owners. *European Journal of Forest Research* **130**(3): 369–381.

Niedziałkowski, K., Paavola, J. & Jędrzejewska, B. (2012) Participation and protected areas governance: the impact of changing influence of local authorities on the conservation of the Białowieża Primeval Forest, Poland. *Ecology and Society* **17**(1): 2

Nijnik, M. (2004) To an economist's perception on sustainability in forestry-in-transition. *Forest Policy and Economics* **6**(3–4): 403–413.

Nijnik, M., Nijnik, A. & Bizikova, L. (2009) Analysing the development of small-scale forestry in Central and Eastern Europe. *Small-Scale Forestry* **8**(2): 159–174.

Olofsson, P., Kuemmerle, T., Griffiths, P., Knorn, J., Baccini, A., Gancz, V., Blujdea, V., Houghton, R.A., Abrudan, I.V. & Woodcock, C.E. (2011) Carbon implications of forest restitution in post-socialist Romania. *Environmental Research Letters* **6**(4): 045202.

Pal, M. & Mather, P.M. (2005) Support vector machines for classification in remote sensing. *International Journal of Remote Sensing* **26**(5): 1007–1011.

Panayotov, M., Kulakowski, D., Laranjeiro Dos Santos, L. & Bebi, P. (2011) Wind disturbances shape old Norway spruce-dominated forest in Bulgaria. *Forest Ecology and Management* **262**(3): 470–481.

Popa, I. (2008) Windthrow risk management: results from Romanian forests. In: *Disturbi in foresta ed effetti sullo stock di carbonio: il problema della non permanenzai, Pubblicazionedel Corso di Cultura in Ecologia, Atti del 44° corso*, ed. T. Anfodillo, E. Dalla Valle & E. Valese, pp. 77–88. Padova, Italy: Università di Padova.

Price, M.F., Gratzer, G., Duguma, L.A., Kohler, T., Maselli, D. & Romeo, R. (2011) Mountain forests in a changing world: realizing values, addressing challenges. Report,.FAO/MPS and SDC, Rome, Italy.

Rozylowicz, L., Popescu, V., Pătroescu, M. & Chişamera, G. (2011) The potential of large carnivores as conservation surrogates in the Romanian Carpathians. *Biodiversity and Conservation* **20**(3): 561–579.

Savulescu, I. & Mihai, B. (2011) Geographic information system (GIS) application for windthrow mapping and management in Iezer Mountains, Southern Carpathians. *Journal of Forestry Research* **23**(2): 175–184.

Schelhaas, M.J., Nabuurs, G.J. & Schuck, A. (2003) Natural disturbances in the European forests in the 19th and 20th centuries. *Global Change Biology* **9**(11): 1620–1633.

Schneider, A. & Ingram, H. (1990) Behavioral assumptions of policy tools. *Journal of Politics* **52**(2): 510–529.

Schulze, E.-D., Hessenmoeller, D., Knohl, A., Luyssaert, S., Boerner, A. & Grace, J. (2009) Temperate and boreal old-growth forests: how do their growth dynamics and biodiversity differ from young stands and managed forests? In: *Old-Growth Forests*, ed. C. Wirth, G. Gleixner & M. Heimann, pp. 343–366. Berlin and Heidelberg, Germany: Springer.

Smith, K.J., Keeton, W.S., Twery, M.J. & Tobi, D.R. (2008) Understorey plant responses to uneven-aged forestry alternatives in northern hardwood–conifer forests. *Canadian Journal of Forest Research* **38**(6): 1303–1318.

Splechtna, B.E., Gratzer, G., Black, B.A. & Franklin, J. (2005) Disturbance history of a European old-growth mixed-species forest: a spatial dendro-ecological analysis. *Journal of Vegetation Science* **16**(5): 511–522.

Svoboda, M., Janda, P., Nagel, T.A., Fraver, S., Rejzek, J. & Bače, R. (2012) Disturbance history of an old-growth sub-alpine *Picea abies* stand in the Bohemian Forest, Czech Republic. *Journal of Vegetation Science* **23**(1): 86–97.

Thompson, I., Mackey, B., McNulty, S. & Mosseler, A. (2009) *Forest Resilience, Biodiversity, and Climate Change. A Synthesis of the Biodiversity/Resilience/Stability Relationship in Forest Ecosystems*. Montreal, Canada: Secretariat of the Convention on Biological Diversity.

Toader, T. & Dumitru, I. (2005) *Romanian forest - national parks and natural parks*. Bucharest, Romania: National Forest Administration ROMSILVA.

Turner, M.G., Wear, D.N. & Flamm, R.O. (1996) Land ownership and land-cover change in the southern Appalachian highlands and the Olympic peninsula. *Ecological Applications* **6**(4): 1150–1172.

Turnock, D. (2002) Ecoregion-based conservation in the Carpathians and the land-use implications. *Land Use Policy* **19**(1): 47–63.

UNDP (2004) UNDP Project document: strengthening Romania's Protected Area system by demonstrating public-private partnership in Romania's Maramures Nature Park. Report, Government of Romania and United Nations Development Programme, Romania.

UNEP (2007) Carpathians environment outlook. Report, United Nations Environment Programme, Geneva, Switzerland.

Veen, P., Fanta, J., Raev, I., Biriş, I.-A., de Smidt, J. & Maes, B. (2010) Virgin forests in Romania and Bulgaria: results of two national inventory projects and their implications for protection. *Biodiversity and Conservation* **19**(6): 1805–1819.

Wirth, C. (2009) Old-growth forests: function, fate and value. A synthesis. In: *Old-Growth Forests*, ed. C. Wirth, G. Gleixner & M. Heimann, pp. 465–491. Berlin and Heidelberg, Germany: Springer.

Wirth, C., Gleixner, G. & Heimann, M. (2009*a*) Old-growth forests: function, fate and value. An overview. In: *Old-Growth Forests*, ed. C. Wirth, G. Gleixner & M. Heimann, pp. 3–10. Berlin and Heidelberg, Germany: Springer.

Wirth, C., Messier, C., Bergeron, Y., Frank, D. & Fankhänel, A. (2009*b*) Old-growth forest definitions: a pragmatic view. In: *Old-Growth Forests*, ed. C. Wirth, G. Gleixner & M. Heimann, pp. 11–33. Berlin and Heidelberg, Germany: Springer.

Wulder, M. (1998) Optical remote-sensing techniques for the assessment of forest inventory and biophysical parameters. *Progress in Physical Geography* **22**(4): 449–476.

Young, J.E., Sanchez-Azofeifa, G.A., Hannon, S.J. & Chapman, R. (2006) Trends in land cover change and isolation of protected areas at the interface of the southern boreal mixedwood and aspen parkland in Alberta, Canada. *Forest Ecology and Management* **230**(1–3): 151–161.

Żmihorski, M., Chylarecki, P., Rejt, Ł. & Mazgajski, T. (2010) The effects of forest patch size and ownership structure on tree stand characteristics in a highly deforested landscape of central Poland. *European Journal of Forest Research* **129**(3): 393–400.