Long-term forest dynamics in mountain regions – accounting for topography, land use history and management regimes to identify high conservation-value ecosystems

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Catalina Munteanu
University of Wisconsin-Madison

Abstract

Forest change is a main component of global change, strongly affecting ecosystem functioning and services. This makes it important to monitor the causes of forest changes, but especially successive forest disturbances (e.g. salvage logging following pest outbreaks) are difficult to track. Similarly, forests that have not been disturbed for long times, such as old-growth forests, are important – but difficult – to map. This is why there is a need to advance remote sensing techniques for forest change assessment in support of conservation.

My goal here is to advance remote sensing and land change science of forest dynamics in mountain areas. Specifically, I will (1) assess the effects of topographic correction on forest change mapping in mountain areas, (2) identify disturbance types, the succession of forest disturbances and their underlying drivers, (3) assess the role of century-long land use legacies in determining the occurrence and extent of recent disturbances, and (4) develop a methodology for old-growth forest mapping based on historic data and Landsat imagery.

I will study the Carpathian region in Eastern Europe because (a) it experienced multiple shifts in forest management over the past century, and (b) very good historic and recent land cover records are available for the region. I will analyze historic maps since the 1860s and available Landsat imagery for 37 footprints to generate annual forest cover mosaics. I will assess the effects of topographic illumination for accurate disturbance mapping. I will employ temporal segmentation algorithms to detect disturbance types, and their dynamics. Using historic maps, I will assess the role of land use legacies in determining recent forest disturbances. Finally, I will develop an object and texture based algorithm for mapping old-growth forests using Landsat satellite imagery and historic maps.

My proposed research pertains directly to NASA's fundamental question of 'How is the Earth system changing and what are the consequences for life on Earth?' and the goals of the NASA LCLUC and the NASA Biodiversity programs. My research will advance remote sensing and land change science by developing methodologies for accurate forest change assessments in mountain regions. My study will enhance the ecological understanding of forest disturbances, and their interactions, as well as the role of land use legacies, and it will support conservation efforts of high value forested areas.

Introduction

The extent and intensity of forest change[1] are a main component of global change[2], affecting climate, biodiversity, and ecosystem services. The processes underlying forest changes are highly complex [1,3,4] as are the spatial and temporal patterns of change, reaching from slow natural succession to abrupt stand replacing disturbances. In the context of conservation planning, it is essential though to track forest change, and especially forest disturbances.

However, change mapping over large area using remote sensing is complicated by several factors. First, in mountain areas, topographic illumination affects reflectance and may impact change assessment[5]. Second, identifying the type and intensity of change may require analyzing dense time series of satellite imagery[6]. Third, forest dynamics occur over decades and centuries, and land use legacies affect recent change[7]. Imprecise forest change assessment, however, affect land management decisions and lead to uninformed conservation decisions. This is why there is a need to further advance methods for remote sensing and land change science, and to analyze long time series of remote-sensing data in conjunction with historic land use data.

With a long and well-documented forest management history, the Carpathian mountains in Eastern Europe represent an ideal "natural experiment" for studying long-term forest change with dense time-stacks in topographically challenging areas. The region harbors some of the largest contiguous old-growth forests in Europe, but their future is at risk[8], and their conservation requires accurate assessments of their extent and change trajectories.

The overarching goal of my research is to advance remote sensing of mountain areas, and land change science in areas with complex forest disturbance patterns. I will focus on high-conservation value forests in the Carpathian region and use a combination of historic maps and dense time-stacks of Landsat imagery to:

Objective 1: assess the effects of topographic correction on forest change mapping in mountain areas;

Objective 2: identify disturbance types (pest outbreaks, windthrows, clearcuts, selective logging) and the succession of disturbances by temporally segmenting annual forest change mosaic stacks;

Objective 3: assess the role of century-long (150 years) land use legacies in determining the occurrence and extent of recent disturbances;

Objective 4: develop a methodology for old-growth forest mapping based on historic data and Landsat imagery.

My research addresses the fundamental NASA question of "*How the land system is changing and what are the consequences for life on Earth*", by addressing questions related to rapid rates of forest change and the related conservation efforts. My results will advance land change science by enhancing the understanding of long term land changes, land use legacies, and their consequences for resource management. My topographic correction procedures will advance remote sensing of mountain areas and clarify the need of mass-processing correction algorithms for Landsat data. Further, I will investigate the succession of forest disturbances (e.g., salvage logging after insect outbreaks) using annual Landsat mosaics. My results will broadly relevant and applicable to any mountainous regions, and for temperate and boreal forest biomes.

Study area

I will study the Carpathian region (~ 400,000 km^2), a naturally and culturally diverse mountain region in Eastern Europe (Fig 1). This is a global biodiversity hotspot, with rare old-growth[9] ecosystems[10] and many wildlife species of conservation concern[11]. However, the extent of old-growth forests is unclear[8,12], and both land use history[13] and forest management[7] complex.

I recently published a meta-analysis of long-term land change across the Carpathians, and found widespread deforestation during the Austro-Hungarian monarchy, and intensive logging during socialism[7]. Since the collapse of the Soviet Union, reforestation on abandoned fields was widespread, and forests shifted from mixed and coniferous to broadleaf forests[9], but disturbances, such as illegal clear cuts, selective logging and wind throws were also common[9].

Approach

Objective 1: Assess the effects of topographic correction on forest change mapping in mountain areas

Illumination effects of mountain topography alter reflectances and can lead to misclassifications and low accuracy. My goal is to assess the effect of topographic corrections on forest change trajectories to support accurate forest change assessments in mountain regions.

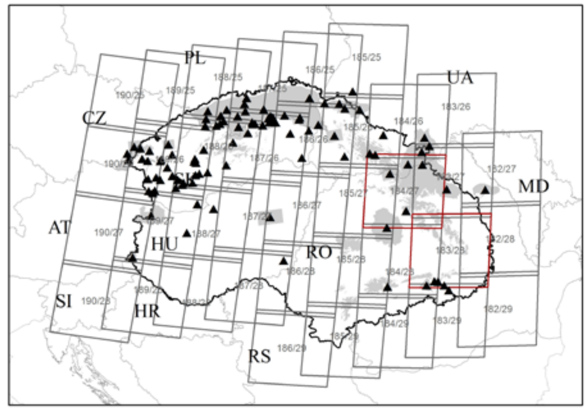

Figure 1 Location of study area in Eastern Europe, extent and centroids of past land change studies (*Munteanu, in press*) and Landsat footprints to be used in this study.

I will assess the usefulness of topographic correction for forest change detection by using annual Landsat TM/ETM+/OLI imagery for 2 footprints (Fig 1) and will generate topographically corrected, seasonally and radiometrically consistent image stacks from 2000-13. I will use only peak-of season imagery (June-September) with <70% cloud cover and where annual data is missing, I will use the nearest available observation. I will apply two individual pre-processing algorithms. First, I will use the Landsat Ecosystem Adaptive Processing System (LEDAPS)[14] for atmospheric correction. Second, I will perform both atmospheric and topographic correction using ATCOR3, a software program that removes jointly topographic and atmospheric effects[15,16]. I will test the correction algorithms using SRTM and also TanDEMx elevation models, because of its higher accuracy and 12m resolution[5]. I will compare the effects of topographic correction on Landsat 6/7 data and on the 12-bit radiometric resolution Landsat 8 data. I will use Fmask[17] with conservative dilation parameters, to mask clouds and shadows, and the Multivariate Alteration Detection algorithm to normalize images[18]. I will calculate Tasseled Caps[19] and compute the Disturbance Index (DI)[20] for both situations. I will use annual time-stacks as input for the temporal segmentation and fitting algorithms[6], and will describe the timing and magnitude of forest disturbances between 2000 and 2013. By comparing the variability in the DI with different pre-processing steps, I will elucidate the importance of topographic correction for forest change detection in mountain areas. I will estimate the magnitude of errors in forest change assessments due to topography, and highlight if operational correction of Landsat imagery for topographic effects is a necessary step in mass data pre-processing. If correcting for topographic illumination improves the results, I will implement the method in my next objectives.

Results from my first objective will make two major contributions. First, I will advance remote sensing science by assessing the importance of topographic correction for forest assessments in mountainous areas. Specifically, I will test the applicability of the analysis module ATCOR3 for Landsat imagery. Second, I will produce topographically corrected imagery and forest disturbance maps for 2000-2103 which is a dataset of vital importance for land management planning and conservation in the area.

Objective 2: Types of forest and the succession of disturbance across the Carpathians based on temporal segmentation of annual mosaic stacks

Salvage logging is common practice following natural disturbances such as windthrows, fires or insect outbreaks[21] but controversial, because the ecological and biodiversity impacts of salvage logging are often higher than those of natural disturbances[22,23]. Salvage logging is common in the Carpathians, and clear cuts are often larger than the initial natural disturbance. Many large clear-cuts are the result of either loopholes in regulations or illegal logging[8,12,24]. However, which portion of all disturbance is due to salvage logging is unclear due to the lack of annual data[9,25,26] and disturbance trajectories.

My goal for my 2nd objective is thus to map forest disturbance types and their trajectories for the Carpathians from 2000-'13. I will focus in particular on the succession of disturbances. I will use Landsat TM/ETM+ imagery for 37 Landsat footprints (Fig 1) and generate seasonally and radiometrically consistent annual Landsat image mosaics[9] from 2000-13 for the Carpathian region (Fig 1, >1000 images/year with <70% cloud cover are available). Where annual data is missing, I will integrate data from the European Landsat archives (if transferred to EROS by then) or use the nearest available observations. I will also quantify how missing data may affect my change assessment. Based on results from Obj. 1, I will decide whether to apply topographic correction and will composite annual image mosaics using the best observation selection algorithm that accounts for acquisition date and distance to cloud[9].

I will map disturbance types including insect defoliation, snow or windthrows, selective logging, and clear cuts, as well as their interactions. I will apply a temporal segmentation algorithm[6] to the spectral change trajectory of each pixel's Tasseled Cap indices[27]. The segmentation applies sequences of straight segments to the spatial and temporal patterns of the spectral trajectory[6] to identify both abrupt disturbances (due to logging or storms), and gradual loss in vegetation vigor (due to insects or selective logging). This is how the dense time-stacks will allow me to track the succession of different types of disturbances, and whether clear-cuts are preceded by insect outbreaks. I will validate my results with high resolution imagery from Google Earth, and with ground truth data collected in field campaigns and available from in-country collaborators (*see letter*).

My results will be broadly relevant to understanding the patterns of natural disturbances and logging – an issue that can only be addressed with annual remote sensing data. The temporal segmentation approach using annual data would be applicable in regions such as Canada, North America, Russia, Indonesia, and Australia where salvage logging is common[21]. For the Carpathians, I will produce annual forest disturbance type maps from 2000-2013. These maps will be important for regional forest management and land use planning, and will support conservation efforts.

Objective 3: Historic forest change and the role of land use legacies in determining the occurrence of recent forest disturbances

Land use has changed landscapes over centuries[28], recent forest composition and patterns are an artefact of past human activity[29,30], and the legacies of past land uses can persist for centuries[31]. However, it is unclear how much these legacies matter, partly because of the lack of historic land use data. For the Carpathians, historical maps starting already in the 1860s[32], together with my Landsat-based forest maps (Obj. 2) provide a unique opportunity to address this issues.

My main goal for my 3rd objective is to quantify the role of land use legacies for subsequent forest disturbances. I hypothesize forest disturbance after 2000 was more likely in areas disturbed between 1860-2000 than in undisturbed areas. Furthermore, I hypothesize that the longer an area has been non-forested, the more likely it is to be recently disturbed. I expect that past and recent forest ownership influences the extent and location of disturbances. To address these questions, I will conduct a spatially-explicit, broad-scale analysis of land change based on historic maps from the 1890s, 1930s, 1960s[32] and my Landsat data (Fig 3). Land cover data for 1890s, 1930s, and 1960s have been digitized from historic topographic maps by collaborators (*see letter*). I will use Map Comparison Kit (MCK), a fuzzy change detection algorithm that resembles human map comparisons[33]. I will quantify the relative importance of past land-use history and past forest ownerships in determining current forest change using logistic regressions and their odds-ratio values[34]. My model will include continuous and categorical variables on the environmental, socio-political and demographic contexts of the region and the historic land cover types. I will check for multi-collinearity and spatial autocorrelation and select variables based on best subset logistic regression[34].

My results will be broadly relevant to land change science and to land management in the Carpathians. First, my forest change models could be applied to any region with long land use records to identify the role of land use legacies for recent forest change. Second, I will produce forest maps since 1860s for the Carpathians, which will serve to understand past land use legacies, predict future ones, and to inform the mapping of old-growth forests (Obj. 4).

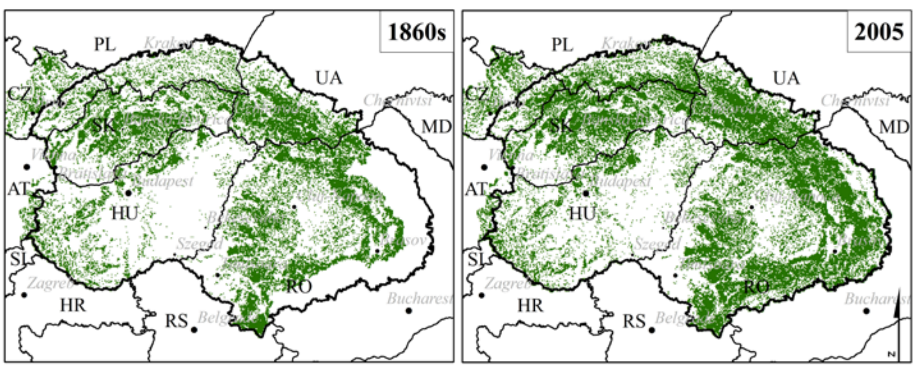

Figure 2. Preliminary results for historic forest cover (1860s) and Landsat (2005).

Objective 4: Mapping old-growth forests, using a combination of historic data and Landsat imagery derived measures of reflectance, image texture and objects

Despite high rates of forest disturbance, the Carpathian mountains still harbor some the largest old-growth forests in Europe[8], but they are at risk[8], and a good assessment of old-growth forests is missing. Previous efforts to map old-growth forest with Landsat elsewhere provide some suggestions for indices and classification algorithms[35–38]. However, both forest structure and data availability are very different in Eastern Europe.

My goal for my 4th objective is to determine the spatial distribution and extent of old-growth forests in the Carpathians. Based on 2 Landsat footprints with good validation data availability (Fig 1), I will develop a mapping algorithm to map old-growth, using dense stacks of forest maps, measures of image texture and composition, and historic maps.

Old-growth forests have typically many large old trees, a large deadwood component (both standing and downed), are dominated by late-successional tree species, and have complex structure[39]. Carpathian old-growth forests consist of a high species diversity dominated by beech and spruce[40]. Based on these characteristics, I will segment the imagery and classify old growth forests [9] from the Landsat mosaics reflectances (Obj. 2) NDVI and Tasseled Cap bands, and

Operational Land Imager (OLI) panchromatic 15m band image texture. I will use eCognition[41,42] to identify homogeneous parts of the image with respect to some characteristic such as greenness, wetness and texture [43,44]. Further, I will incorporate two temporal measures of forest persistence: no-significant change in Tasseled Cap Wetness and NDVI after temporal segmentation (Obj. 2) and no change in forest cover since 1860s (Obj. 3). For validation, I will collect ground-truth data at 50 sites as well as data provided by local forest managers. I will compare my results with national old-growth forest maps[45], with unknown reliability[8,12].

Using my methodology I will be able to map old-growth forests at regional scales in the Carpathians. My results will consist of old-growth forest maps based on Landsat data, which will support conservation efforts. Further, I will advance remote sensing and conservation biology by providing the algorithms for mapping high-value forest ecosystems in any areas with good spatial and temporal data availability such as the US, Central and Latin America or Russia.

Expected outcomes

A NASA ESSF would allow me to build a strong scientific foundation for my future career, in which I will conduct interdisciplinary research at the interface of remote sensing, land change science, and conservation biology. In addition to two publications stemming from the preparatory analysis for my dissertation[7,9] I will publish four peer-reviewed journal articles:

1. The role of topographic correction in mountain areas for accurate forest change assessments – *Remote Sensing of Environment*
2. Disturbance succession in the Carpathians – mapping forest management decisions with annual temporal segmentation of Landsat mosaics – *Remote Sensing of Environment*;
3. The role of land use legacies in modulating recent forest disturbances: lessons from the Carpathians: *Annals of the Association of American Geographers*
4. Mapping old-growth forests with historic maps and Landsat imagery – *Conservation Biology*.

In addition, my research will generate datasets relevant to forest management and conservation in the Carpathians, which I will make openly and freely available: (1) annual forest cover mosaics for 2000-2013, (2) historic land cover maps for 1860s, 1930s, 1960s, (3) old-growth forest map for the year 2013. My methods will be generally applicable by remote sensors and conservationists interested to map forest dynamics in any topographically challenging areas.

I will use data from several NASA assets including Landsat TM/ETM+/OLI imagery for 37 footprints (Fig 1), SRTM elevation data, and NASA-funded software tools like LEDAPS and Fmask. I will use these in conjunction with other remote sensing tools such as ATCOR3 or TanDEMx, which will integrate European and U.S. remote sensing technologies and products. Last but not least, I will collaborate closely with a network of partners in the region, thus building capacity, and strengthening international collaborations.

Overall Significance

In terms of its scientific contribution, my research will advance our understanding of coupled human-natural systems, especially broad-scale forest change in relation to land use legacies. My study employs new technologies that will advance land change monitoring using dense temporal Landsat stacks as well as historic data. It will clarify to what extent land use legacies modulate the extent of recent land change, enhancing our understanding of land transition theories. Furthermore, it will clarify questions related to the succession of disturbances and their ecological significance, addressing directly NASA's fundamental question of "*How is the Earth system changing and what are the consequences for life on Earth*?"

The Carpathian region, with its long and well documented land use history, multiple shifts in forest management and topographically challenging terrain, represents the ideal 'natural experiment' for developing new forest remote sensing approaches. My research will clarify the value of topographic correction of Landsat data. My temporal segmentation approach will enhance the ability to identify forest disturbance types, and their succession at broad scales. From an applied perspective, my results will inform forest management and conservation planning by providing the first independent broad-scale assessment of the extent and location of old-growth forests in the Carpathians. The effects of individual management decisions can be assessed based on the annual forest disturbance maps.

As such, my interdisciplinary research will pertain to NASA's Earth Science Research Program, and to four of the major international initiatives related to land use change science, the NASA LCLUC program, and particularly the SCERIN (South East and Central Europe Research and Information Network) initiative, NEESPI (Northern Eurasia Earth Science Partnership Initiative), GOFC-GOLD (Global Observation of Forest and Land Cover Dynamics), and GLP (Global Land Project), contributing to the overall goal of enhancing management and practical application of land cover and terrestrial ecosystems scientific products.

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Project timeline - NESSF2014

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Task	**2014**			**2015**				**2016**				**2017**			
	II	**III**	**IV**	**I**	**II**	**III**	**IV**	**I**	**II**	**III**	**IV**	**I**	**II**	**III**	**IV**
Metaanalysis	P														
Data preprocessing Objective 1	F														
Analysis Objective 1															
Writing Objective 1						S									
Data preprocessing Objective 2															
Analysis Objective 2															
Writing Objective 2									S						
Data preprocessing Objective 3															
Analysis Objective 3															
Writing Objective 3													S		
Data preprocessing Objective 4									F						
Analysis Objective 4															
Writing Objective 4															S
Dissertation															S

P Paper publication

S Planned submission of paper/ dissertation

F Field data collection and collaborator meetings